AFRL-RZ-WP-TP-2009-2177

DISTRIBUTED CONTROL OF TURBOFAN ENGINES (POSTPRINT)

Mehrdad Pakmehr, Marion Mounier, Nathan Fitzgerald, George Kiwada, James D. Paduano, Eric Feron, and Alireza Behbahani

Georgia Institute of Technology

AUGUST 2009

Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
PROPULSION DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
August 2009	Conference Proceedings Postprint	31 August 2008 – 01 August 2009

4. TITLE AND SUBTITLE
DISTRIBUTED CONTROL OF TURBOFAN ENGINES (POSTPRINT)

5a. CONTRACT NUMBER FA9550-08-C-0052

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 65502F

6. AUTHOR(S)
Mehrdad Pakmehr, Marion Mounier, and Eric Feron (Georgia Institute of Technology)
Nathan Fitzgerald, George Kiwada, and James D. Paduano (Aurora Flight Sciences Corporation)
Alireza R. Behbahani (AFRL/RZTF)

5d. PROJECT NUMBER N/A

5e. TASK NUMBER N/A

5f. WORK UNIT NUMBER N/A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Georgia Institute of Technology
Atlanta, GA 30332

Aurora Flight Sciences Corporation
Manassas, VA 20110

Fan and Compressor Branch (AFRL/RZTF)
Turbine Engine Division
Air Force Research Laboratory, Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command, United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/RZTF

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RZ-WP-TP-2009-2177

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Conference proceedings of the 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2-5 Aug 2009, Denver, CO.
PAO Case Number: 88ABW-2009-3525, 01 Jul 2009. Paper contains color, text, and briefing charts.
The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

14. ABSTRACT
The purpose of this paper is to develop control theoretic concepts for distributed control of gas turbine engines, and develop a dynamic engine model incorporating distributed components in compressor dynamics, engine cycles, and engine control. The latest results in distributed control combined with adaptive control theory are extended for turbofan engine distributed control. Concepts and architectures for distributed control are developed that create tangible benefits from the distribution of closed-loop feedback around the engine.

15. SUBJECT TERMS
stability of distributed engine control systems, decentralized distributed, decentralized framework, packet dropping, improving the stability

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)	19b. TELEPHONE NUMBER *(Include Area Code)*
Unclassified	Unclassified	Unclassified	SAR	62	Alireza R. Behbahani	N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2-5 Aug 2009, Denver, Colorado

Distributed Control of Turbofan Engines

Mehrdad Pakmehr* and Marion Mounier†
Georgia Institute of Technology, Atlanta, GA 30332

Nathan Fitzgerald‡ and George Kiwada § and James D. Paduano ¶
Aurora Flight Sciences Corporation, Manassas, VA 20110

Eric Feron‖
Georgia Institute of Technology, Atlanta, GA 30332

Alireza Behbahani**
Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio 45433

The purpose of this paper is to develop control theoretic concepts for distributed control of gas turbine engines, and develop a dynamic engine model incorporating distributed components in compressor dynamics, engine cycles, and engine control. The latest results in distributed control combined with adaptive control theory are extended for turbofan engine distributed control. Concepts and architectures for distributed control are developed that create tangible benefits from the distribution of closed-loop feedback around the engine.

I. Introduction

Engineers and researchers[1] agree that the next-generation engine controls need to move to a distributed architecture in order to increase flexibility through common standards, improve redundancy properties by improving the overall system topology, and enable component self-diagnosing and other benefits of 'smart' actuators and sensors, such as reduced harness weight. In this vision, distributed computing in the smart components allows for localization of A/D conversion and signal processing, supports open standards and modularity, and provides an opportunity for self-diagnosis. This however is still a somewhat limited use of distributed computing capabilities: The smart components neither close any local control loops, nor perform any functions effecting the stability or performance of the engine. Thus the Full Authority Digital Engine Controller (FADEC) still remains the central arbiter of the engine's dynamic behavior, performance, and reliability.

The problem we will address in this effort is the need to go beyond the limited application of distributed computing. This need arises because the full potential of a distributed architecture cannot be attained unless the control algorithms themselves are distributed. For instance, if the control laws are not distributed the dependence on the FADEC remains high, and system reliability can only be insured through many redundant components and interconnections. Information-flow and redundancy requirements are still based on a centralized controller, and the potential for complex and hard-to-modify centralized code remains. Furthermore, the benefits of adaptation, robustness, and self-repair at the component level are not attained.

*PhD Candidate, School of Aerospace Engineering, Mehrdad.Pakmehr@gatech.edu, AIAA Student Member.
†MS Student, School of Industrial and Systems Engineering, marion.mounier@gatech.edu
‡Propulsion Engineer, Aurora Flight Sciences Corporation, nfitzgerald@aurora.aero.
§Propulsion Engineer, Aurora Flight Sciences Corporation, gkiwada@aurora.aero.
¶Principal Investigator, Aurora Flight Sciences Corporation, jpaduano@aurora.aero, AIAA Member.
‖Professor, School of Aerospace Engineering, feron@gatech.edu, Associate Fellow AIAA.
**Senior Aerospace Engineer, Air Force Research Laboratory, al.behbahani@wpafb.af.mil, Associate Fellow AIAA

Such properties are best achieved through feedback control at the component level and have the potential to improve overall system reliability.

Previous work on distributing the control algorithms in gas turbine engines has not taken advantage of recent progress in adaptive control algorithms. An adaptive controller requires little or no a priori information about the unknown parameters, improves its performance as it adapts, and is likely to use lower gains since adaptation extends on to the level that is necessary instead of to a conservative pre-determined level. The probable advantages of adaptive control are particularly applicable to distributed control in gas turbine engines as they can probably help overcome communication imperfections such as lag or packet drop inherent in a networked control architecture.

To determine the feasibility of a distributed adaptive engine control approach, a systematic evaluation is needed of the stability and performance characteristics that would result if not only sensors and actuators but entire subsystems of the engine become 'smart'; that is, if distributed computing is used at the local level and only coordinated by the FADEC. Such an architecture must be studied in the context of noisy, band-limited and delayed communications between the subsystem controllers. Furthermore, the impact of varying operating conditions on the performance at the global level of the hierarchical control system must be addressed. Finally, the potential for instabilities due to the interaction of separate controllers when delays and synchronization issues arise must also be addressed.

Distributed control is a broad term that encompasses many different levels of control delegation from the traditional FADEC. As the signal processing and control laws are distributed further there are also different configurations in which engine components can be grouped for control. Some sample distributed control architectures are compared with a FADEC in figure 1. Benefits from distributed control, such as sensor modularity, weight reduction, and life-cycle cost reduction have been discussed in previous works.[1–3] An appealing configuration is the Partially Distributed control architecture, where there are local controllers with some authority but the entire engine system is still governed by a central supervisory controller. Partially distributed control has many of the benefits of fully distributed control but retains a central supervisor to communicate with the operator and handle some system level tasks such as engine start up. Partially distributed control architecture enables a new engine development paradigm infeasible with less distributed control schemes.

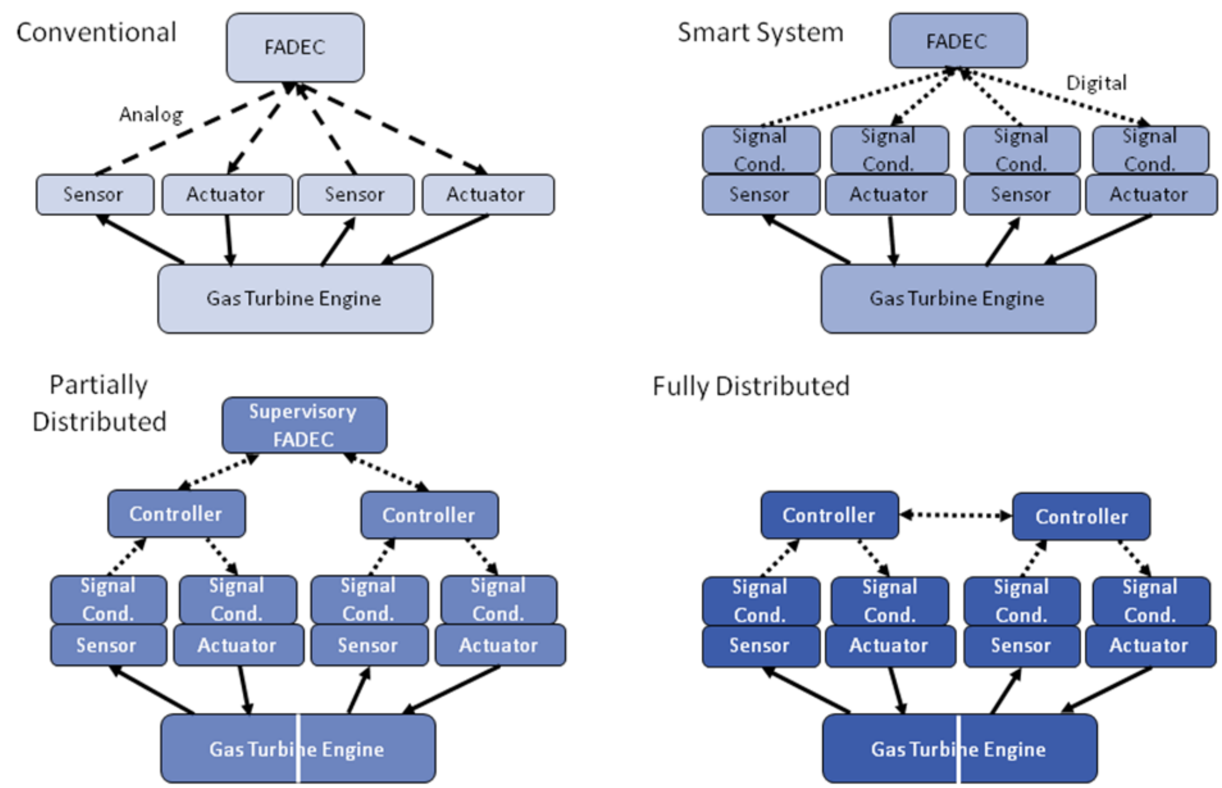


Figure 1. Control Architecture Diagrams for a Gas Turbine Engine

The new engine development scenario envisioned here has gas turbine engine cores being utilized in a more modular manner similar to the current use of internal combustion (IC) engines. As an illustrative example consider a simple IC engine Helicopter. The IC engine is purchased with its own governor or Engine Control Unit (ECU) and connected via a transmission to the rotor, a variable load. The operator has control over the engine RPM as well as the engine load (via the rotor). Applying this analogy to a gas turbine instead of a helicopter the IC engine represents a gas generator core (High Pressure Compressor (HPC), combustor, High Pressure Turbine (HPT)), the rotor load represents either a shaft driven device or even a new spool (Fan, Low Pressure Turbine (LPT)), and the operator is a supervisory controller. Creating a separate engine controller for the gas generator has strong commercial applications, both in large scale commercial gas turbine design and small scale UAV development.

Commercial manufacturers of Gas Turbine engines rarely design all new engine centerlines,[4] the lifespan of successful engine families lasts decades. Many of the new engines designed in a family are based on an existing engine core, primarily due to cost and reliability concerns. The high pressure compressor and turbine contain the highest performance, and therefore most expensive, components. Engine core designs may move from military turbojets into commercial turbo-fans and turbo-props.[5] In the case of the extremely popular CFM56 (figure 2) a GE F101 engine was used as the core for a different company's engine.

Figure 2. CFM56 engine developers by component[6]

Distributed adaptive engine control could enable "plug and play" development of entire families of engines. In the distributed engine control vision engine cores could be purchased with onboard subordinate controllers ready for integration into a larger engine, whereas the CFM56 FADEC was developed independently for the integrated engine. Structuring engine control in such a distributed fashion would increase compatibility between different engine manufacturers and reduce development time and cost for new engines.

A similar niche is occurring in UAV development, where small gas turbines are being used to power a variety of different lift/thrust devices. UAV development programs rarely have the resources for serious engine redevelopment and therefore must select from a limited number of commercial off the shelf (COTS) engines. In the case of small gas turbines these COTS engines are generally designed for missile-turbojet or power generator applications, while the UAV designer may want to use the engine core in a turbo-prop or turbofan application. Successful development of adaptive distributed control for this class of engines would allow UAV designers to purchase engines with onboard controllers and mate them with their own proprietary fan/prop sections without having to design a new control system from scratch.

In this paper we demonstrate the feasibility of a partially distributed control scheme with separate controllers on the engine core and fan, where the controllers are linked by a supervisory controller. This scheme is representative of the situation encountered in VTOL UAV design and the design of new turbo-props and variable pitch turbofans by the large commercial gas turbine manufacturers. For future we will develop the partially distributed controller further to cover safe performance during non standard operations (including sensor failure etc.), culminating in a static engine test of a small turbo-prop engine running the developed distributed adaptive controller.

II. Engine Model

A. Overview

For the purpose of the distributed control analysis we use a simplified dynamic model of a generic turboshaft engine driving a lift fan, depicted in Figure 3. Fuel is provided to the core of the engine, which is comprised of a compressor, combustor, and turbine. The turbomachinary components are connected by a shaft that also provides torque to the fan by way of a reduction gearbox. The thrust from the fan can be controlled by varying the pitch angle of the fan blades, or by varying the exit area of fan duct.

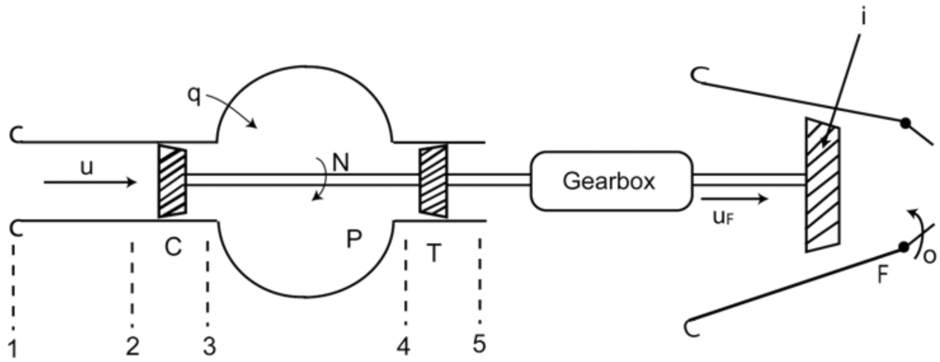


Figure 3. Turbofan engine diagram

The dynamics of thrust and efficiency are modeled using the lumped-parameter, first-principles approach common to standard gas turbine textbooks.[7,8] The performance of the core will be represented by the power of the turbomachinary components, which can be described as functions of the inlet temperatures and pressures through the engine, the air flow through the core, pressure ratios across the components, component efficiencies, and temperature in the combustor. The fan performance can be determined from the airflow through the fan, the fan pressure ratio, and inlet temperature and pressure.

The model of the engine system for this phase uses the following assumptions and simplifications:

- Only the dynamics of the spool will be considered. Other low speed dynamics, like heat transfer from the gas path to metal, or higher speed dynamics, such as acoustics, volume dynamics, and combustor heat release dynamics, are ignored in the current analysis. The essential role of the engine controller can be assessed from this perspective, and in future phases of the project more detailed dynamics can be modeled if necessary.

- The analysis will assume sea level static operation of the engine system, typical of a hovering condition for a VTOL UAV.

- The turbine expands the exhaust gases of the core perfectly to ambient pressure, such that all possible work is extracted from the flow. The exhaust of the core is assumed to have no impact on the thrust produced by the fan.

- Non-ideal efficiencies are assumed for the fan, compressor, combustor, and turbine, but all other components are assumed to operate ideally. In particular, there is no pressure loss in the inlets the core and fan, and the fan nozzle is assumed to allow perfect expansion of the fan airflow back to ambient pressure.

- The core is modeled as a simple gas generator with no secondary or bleed flows for turbine cooling or other uses.

- The mass and temperature of the fuel is ignored in the calculations. The fuel is simply modeled as adding heat to the thermodynamic cycle in accordance with its mass flow rate and heat of combustion.

- The calculations assume that the specific heat of the air going through both the core and the fan is independent of temperature.

B. Detailed Description

In the model presented here, the performance of the engine system is a function of several lumped-parameter thermodynamic variables. For the core, these are the corrected mass flow through the compressor (W_c), the compressor pressure ratio (π_c), and the ratio of turbine inlet stagnation temperature to the compressor inlet stagnation temperature (T_4/T_2). For the fan, the key thermodynamic parameters are the corrected mass flow (W_f) and the pressure ratio (π_f). For a given inlet stagnation temperature and pressure (T_2 and P_2), the thrust and the fuel consumption of the engine can be set. The spool speed, N, is the mechanical constraint that links the thermodynamic condition of the individual components to each other.

The dynamics of the spool can be described from Newton's second law by the sum of the torques produced by the turbomachinary components ($\mathcal{T}$), as well as the overall rotational inertia of the system (I).

$$I\dot{\omega} = \mathcal{T}_t - \mathcal{T}_c - \mathcal{T}_f. \tag{1}$$

Here, ω is expressed in rad/s and the subscripts t, c, and f represent the turbine, compressor, and fan respectively. Noting that the power output of each of those components is defined by $\mathcal{P} = \mathcal{T}\omega$ and expressing the key parameters as a fraction of the design value, Equation 1 can be rewritten as

$$\frac{\dot{N}}{N_{des}} = \left(\frac{60}{4\pi^2}\frac{\mathcal{P}_{des}}{IN_{des}^2}\right)\left(\frac{\mathcal{P}_t}{\mathcal{P}_{t,des}}\frac{\mathcal{P}_{t,des}}{\mathcal{P}_{des}} - \frac{\mathcal{P}_c}{\mathcal{P}_{c,des}}\frac{\mathcal{P}_{c,des}}{\mathcal{P}_{des}} - \frac{\mathcal{P}_f}{\mathcal{P}_{f,des}}\right) / \left(\frac{N}{N_{des}}\right), \tag{2}$$

where the rotational speed (N) has been expressed in rpm instead of rad/s. The expression of the performance parameters as a ratio of their design values allows the analysis to circumvent the knowledge of several detailed parameters in the cycle. For instance, the gear ratio of the gearbox is not required in this representation. The power output of each of those components is determined by the thermodynamic matching of the engine.

The power requirement of the compressor is equal to the enthalpy increase from station 2 to station 3 in Figure 3, which can be expressed as a function of mass flow, pressure ratio, adiabatic efficiency, and inlet conditions. Written as a fraction of the design power,

$$\frac{\mathcal{P}_c}{\mathcal{P}_{c,des}} = \frac{W_2}{W_{2,des}}\frac{P_2}{P_{2,std}}\sqrt{\frac{T_2}{T_{2,std}}}\frac{\eta_{c,des}}{\eta_c}\frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\pi_{c,des}^{\frac{\gamma-1}{\gamma}} - 1}, \tag{3}$$

assuming constant ratio of specific heats, $\gamma = c_p/c_v$. The mass flow is expressed as corrected flow, or equivalent flow at standard conditions $W = \dot{m}\sqrt{T/T_{std}}/(P/P_{std})$. P is stagnation pressure and η is adiabatic efficiency.

The fan power consumption is exactly analogous to that of the compressor,

$$\frac{\mathcal{P}_f}{\mathcal{P}_{f,des}} = \frac{W_f}{W_{f,des}}\frac{P_2}{P_{2,std}}\sqrt{\frac{T_2}{T_{2,std}}}\frac{\eta_{f,des}}{\eta_f}\frac{\pi_f^{\frac{\gamma-1}{\gamma}} - 1}{\pi_{f,des}^{\frac{\gamma-1}{\gamma}} - 1}. \tag{4}$$

The power provided by the turbine is equal to the energy extracted as the gas is expanded from the combustor exit temperature and pressure back to ambient conditions. Assuming static conditions, the pressure ratio across the turbine is therefore set by the compressor pressure ratio and the burner pressure loss ($\pi_c\pi_b\pi_t = 1$). Assuming that the mass flow through the turbine is equal to that of the compressor, the power output can be calculated as a function of the turbine inlet temperature.

$$\frac{\mathcal{P}_t}{\mathcal{P}_{t,des}} = \frac{W_c}{W_{c,des}}\frac{P_2}{P_{2,std}}\sqrt{\frac{T_2}{T_{2,std}}}\frac{\eta_t}{\eta_{t,des}}\frac{1 - (\pi_c\pi_b)^{\frac{-(\gamma-1)}{\gamma}}}{1 - (\pi_{c,des}\pi_{b,des})^{\frac{-(\gamma-1)}{\gamma}}}. \tag{5}$$

The turbine inlet temperature is determined by the amount of fuel entering the combustor. Ignoring the mass of the fuel and the fuel temperature, the inlet stagnation temperature to the turbine can be calculated from a simple energy balance.

$$\dot{m}_f h_f = \dot{m}_c c_p \left(T_4 - T_3\right). \tag{6}$$

As written, this equation assumes that all of the energy of the fuel is translated to heat in the combustor regardless of equivalence ratio or adiabatic flame temperature of the fuel air reaction. In the actual model code, an upper limit is placed on T_4 near the max adiabatic flame temperature to prevent the simulation from adding a limitless amount of energy into the system. Expressed as a ratio of design values, the effect of fuel flow on turbine inlet temperature can be expressed as

$$\frac{\dot{m}_{fuel}}{\dot{m}_{fuel,des}} = \frac{W_c}{W_{c,des}} \frac{\frac{T_4}{T_2} - \tau_c}{\frac{T_{4,des}}{T_{2,des}} - \tau_{c,des}}. \tag{7}$$

Note that the temperature ratio across the compressor (τ_c) is known from the compressor pressure ratio (π_c) and adiabatic efficiency (η_c).

The power expressions from Equations 3, 4, and 5 are linked together and to the spool speed through mass flow conservation, as well as by the individual component performance maps. In the core, the mass flow is set by the throttling effect of the turbine, where the nondimensional flow through the component is set by the pressure ratio across it. The inlet conditions of the turbine can be expressed as functions of the compressor and combustor performance as follows:

$$\frac{\dot{m}_c\sqrt{RT_4}}{P_4 A_4} = FP_4(\pi_t) = \frac{\dot{m}_c\sqrt{RT_2}}{P_2 A_2} \frac{\sqrt{\frac{T_4}{T_2}}}{\frac{P_3}{P_2}\frac{P_4}{P_3}} \frac{1}{\frac{A_4}{A_2}}. \tag{8}$$

For a fixed design, compressor and turbine inlet areas (A_2 and A_4) are considered constant, so they fall out when the equation is expressed as a ratio of design values.

$$\frac{\pi_c}{\pi_{c,des}} \frac{\pi_b}{\pi_{b,des}} \frac{FP_4}{FP_{4,des}} \sqrt{\frac{T_{4,des}}{T_{2,des}}} = \frac{W_c}{W_{c,des}} \sqrt{\frac{T_4}{T_2}}. \tag{9}$$

To simplify the calculation, the model assumes that the turbine is thermodynamically choked, so FP_4 is constant and equal to the design value. This is a typical assumption made in turbine engine models, and is usually invalid only at engine settings near idle.

For the fan, the feature that controls the mass flow is the nozzle exit area, A_e. Since the nozzle is not choked, the expression for the conservation of mass flow must take the flow parameter variation into account. Writing fan nozzle mass flow as a function of fan inlet and operating conditions, we have

$$\frac{\dot{m}_f\sqrt{RT_e}}{P_e A_e} = FP_e(\pi_f) = \frac{\dot{m}_f\sqrt{RT_2}}{P_2 A_2} \frac{\sqrt{\frac{T_e}{T_2}}}{\frac{P_e}{P_2}} \frac{1}{\frac{A_e}{A_2}}. \tag{10}$$

Dividing the parameters in this equation by their design values, we have

$$\frac{\pi_f}{\pi_{f,des}} \frac{A_e}{A_{e,des}} \frac{FP_e(\pi_f)}{FP_e(\pi_{f,des})} = \frac{W_f}{W_{f,des}} \sqrt{\frac{\tau_f}{\tau_{f,des}}}. \tag{11}$$

The nozzle flow parameter characteristic, $FP_e(\pi_f)$, can be calculated for static conditions assuming ideal expansion to ambient pressure as

$$FP = \sqrt{\frac{2\gamma}{\gamma - 1}\left(\pi^{-\frac{2}{\gamma}} - \pi^{-\frac{\gamma-1}{\gamma}}\right)}. \tag{12}$$

Component maps provide the final link from thermodynamic performance to mechanical state. For the turbine, we assume that the adiabatic efficiency is constant and equal the the design value for the range of conditions to be simulated. For the fan and compressor, the pressure ratio and efficiency of each component is expressed as a function of the spool speed and airflow, both corrected to inlet conditions. The change in incidence angle of the fan blades from the design condition(Δi) is also input to the fan map.

$$\left[\frac{\pi_c}{\pi_{c,des}}, \frac{\eta_c}{\eta_{c,des}}\right] = CompressorMap\left(\frac{W_c}{W_{c,des}}, \frac{N}{N_{des}}/\sqrt{\frac{T_2}{T_{std}}}\right), \tag{13}$$

$$\left[\frac{\pi_f}{\pi_{f,des}}, \frac{\eta_f}{\eta_{f,des}}\right] = FanMap\left(\frac{W_f}{W_{f,des}}, \frac{N}{N_{des}}/\sqrt{\frac{T_2}{T_{std}}}, \Delta i\right). \tag{14}$$

For the purposes of this Phase of investigation, generic maps have been generated for the fan and compressor based on assumed ϕ/ψ characteristics and other aspects of compressor theory. As the model is improved, these generic maps can be replaced with ones representing the performance of specific compressors and fans.

For a given spool speed, the seven unknown parameters of the system ($W_c, W_f, \pi_c, \pi_f, \eta_c, \eta_f$, and T_4/T_2) can be calculated from a system of seven equations, Equations 7, 9, 11, 13 and 14. Note that 13 and 14 represent two equations each. The solution of that system of equations provides all the necessary information to determine the dynamics of the system as expressed in Equation 2.

Lastly, the performance output of the engine system, namely thrust and fuel consumption, can be calculated from the solved system parameters. At static conditions, the thrust from the fan can be approximated from first principles as $F = \dot{m}_f u_e$, where u_e is the velocity of the air exiting the fan,

$$\frac{F}{A_e P_{T_2}} = \gamma M_e^2 = \frac{2\gamma}{\gamma - 1}(\pi_f^{\frac{\gamma-1}{\gamma}} - 1). \tag{15}$$

As a function of design parameters, this becomes

$$\frac{F}{F_{des}} = \frac{A_e}{A_{e,des}} \frac{P_2}{P_{2,des}} \frac{\pi_f^{\frac{\gamma-1}{\gamma}} - 1}{\pi_{f,des}^{\frac{\gamma-1}{\gamma}} - 1}. \tag{16}$$

Specific fuel consumption is follow as the ratio of fuel flow to thrust

$$\frac{SFC}{SFC_{des}} = \left(\frac{\dot{m}_{fuel}}{\dot{m}_{fuel,des}}\right) / \left(\frac{F}{F_{des}}\right). \tag{17}$$

C. Linearized Engine Model

Nonlinear engine model can be represented as

$$\begin{aligned} \dot{x}(t) &= f(x(t), u_1(t), u_2(t), u_3(t)), \\ y(t) &= g(x(t), u_2(t), u_3(t)), \end{aligned} \tag{18}$$

where $x(t)$ is the spool speed and the only state of the system, $u_1(t)$ is the fuel flow control input, $u_2(t)$ is the fan exit area control input and $u_3(t)$ is the fan vane angle control input. Control inputs ranges are $u_1(t) \in [0.3,\ 1.2],\ u_2(t) \in [0.8,\ 1.2]$ and $u_3(t) \in [-10,\ 10](deg)$ which are imposed by physical limitations.

Linearizing this model around design point ($x_{des} = 1, u_{des} = [1,\ 1,\ 0]^T$) we have

$$\delta\dot{x}(t) = a.\delta x(t) + b_1.\delta u_1(t) + b_2.\delta, u_2(t) + b_3.\delta u_3(t), \tag{19}$$

which also can be written as

$$\delta\dot{x}(t) = a.\delta x(t) + b.\delta u(t), \tag{20}$$

where $\delta x = x - x_{des},\ \delta u = u - u_{des}$. For the purpose of closing the loop in the fan subsystem, we defined the thrust as the output and assumed we can estimate it as a linear function of the state, fan vane angle, and fan exit area control inputs.

$$\delta y(t) = c.\delta x(t) + d_1.\delta u_1(t) + d_2.\delta u_2(t) + d_3.\delta u_3(t), \tag{21}$$

where $\delta y = y - y_{des},\ \delta u = u - u_{des}$, where the design value for output is $y_{des} = 1$. Constants are $a = -4.63,\ b_1 = 1.78,\ b_2 = 0.31,\ b_3 = 2.96,\ c = 1.921,\ d_1 = 0,\ d_2 = 0.215,\ d_3 = -1.44$. These values has been found by numerical linearization of the engine dynamics.

III. Distributed Linear Control

For distributed control purpose, we divided the model into two subsystems which are the core engine and the fan. Distributed turbofan engine model is represented in figure 4.[2]

The highlighted subsystems are candidates for simplified, distributed control structure. In our engine model, system I is analogous to the "Inlet Fan", and system II is analogous to the core engine (i.e. Compressor, Combustor, Turbine Nozzle).

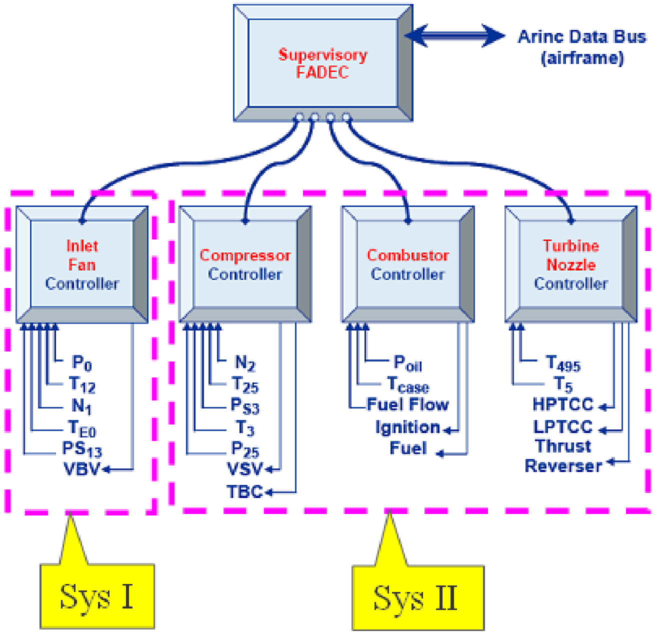


Figure 4. Schematic of turbofan engine subsystems[2]

In this section we design linear controllers for two subsystems based on classical control. The controllers will be I and PI controllers. The figures of merit which we use to quantify the performance are *percent overshoot* (PO) and *settling time* (t_s) for the transient response and *steady state error* (e_{ss}) for the steady state response of the system.

A. Core Controller Design Strategy

Here, we need $x(t)$ track a given smooth trajectory $r_c(t)$, while all other signals remain bounded.

introducing the integral error of spool speed as an additional state into the system dynamics, we have

$$\tilde{x}(t) = \delta x_1(t) - r_c(t), \quad \tilde{x}(0) = 0. \tag{22}$$

The new state will be

$$\delta x_2(t) = x_I(t) = \int_0^t \tilde{x}(\tau)d\tau. \tag{23}$$

The model which we use to control the engine spool speed is developed assuming $\delta u_2(t) = \delta u_3(t) = 0$

$$\begin{aligned} &\delta \dot{x}_1(t) = a.\delta x_1(t) + b_1.\delta u_1(t), \quad \delta x_1(0) = \delta x_2(0) = 0, \\ &\delta \dot{x}_2(t) = \delta x_1(t) - r_c, \end{aligned} \tag{24}$$

where $\delta x_1(t)$ is the spool speed and $\delta x_2(t)$ is the integration of spool speed tracking error.

The linear control logic for fuel flow is

$$\delta u_1(t) = k_{pf}.\delta x_1(t) + k_{if}.\delta x_2(t). \tag{25}$$

B. Decentralized Linear Controller Design Strategy

Decentralized control structure we present here has two subsystems (i.e. core engine and the fan) and we design two linear controllers for each subsystem. Fuel flow is the control input for the core subsystem and vane angle is the control input for the fan subsystem.

1. *Subsystem I: Fan Control Design*

Here, we need $y(t)$ to track a given smooth trajectory $y_c(t)$, while all other signals remain bounded.

Introducing the integral error of the output as an additional state into the system dynamics, we have

$$\tilde{y}(t) = \delta y(t) - y_c(t), \tag{26}$$

where

$$\delta y(t) = c.\delta x_1(t) + d_3.\delta u_3(t), \tag{27}$$

is the linear estimation of the turbofan thrust.

The new state is

$$\delta x_3(t) = y_I(t) = \int_0^t \tilde{y}(\tau) d\tau. \tag{28}$$

Hence the control logic for fan vane angle is

$$u_3(t) = k_{ia}\delta x_3(t), \tag{29}$$

where $\delta x_3(t)$ is the integration of output tracking error. Note that $d_3 < 0$, hence we need a negative gain.

2. *Subsystem II: Core Engine Control Design*

The control for this subsystem is similar to what we explained in the 'core control design strategy' section. We construct the $r_c(t)$ signal from $y_c(t)$ and $\delta u_3(t)$ using the thrust estimation equation. The following relation is used to reconstruct $r_c(t)$ from $y_c(t)$

$$r_c(t) = [y_c(t) - y_{des} - d_3(u_3 - u_{3des})(\pi/180)]/c + x_{des}. \tag{30}$$

The decentralized control structure in which we construct the $r_c(t)$ signal from $y_c(t)$ and $\delta u_3(t)$ using the thrust estimation equation, is shown in figure 5. The signals are shown with solid lines and the mechanical interconnection is shown with a dashed line.

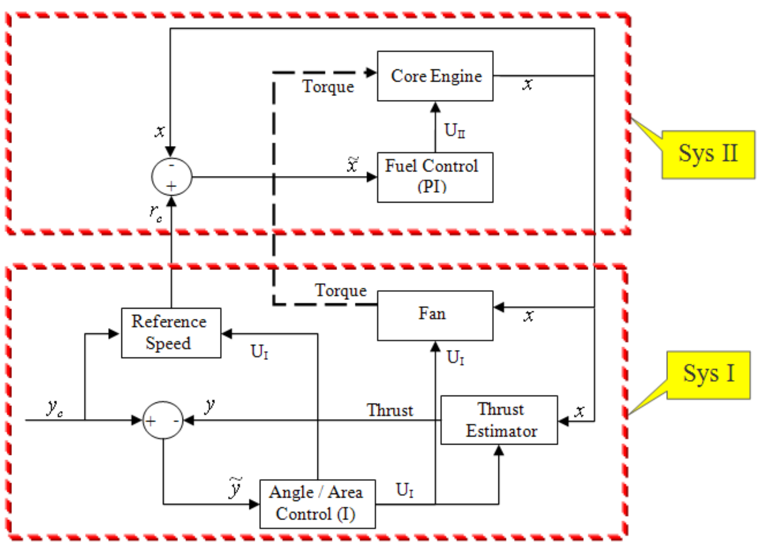


Figure 5. Decentralized linear control structure, $r_c(t)$ signal depends on $y_c(t)$

C. Core Engine Linear Control Results

In this simulation we assumed that torque is a function of time and defined it as $T(t) = 1 + 0.1\sin(1.3(1 + \sin(4t))t)$. The linearized nominal system for this simulation is $\dot{x}(t) = a.\delta x(t) + b.\delta u_1(t) = -1.8\delta x(t) + 1.7460\delta u_1(t)$.The simulation results for linear control of core engine are presented here.

The control parameters and initial conditions for all of these cases are

$$\begin{aligned} k_{pf} = 9, \quad k_{if} = 75, \\ x(0) = 1.0, \quad T(0) = 1.0. \end{aligned} \tag{31}$$

In this simulation $r_c(t)$ is a step signal which defines the reference spool speed to change from 1 to 0.95. Simulation results are shown in figures 6 to 9. Figure 6 shows spool speed history for nominal and reference plant and also state tracking error history. It can be seen that state follows the reference trajectory very closely. Figure 7 shows the history of the load on the core engine. Figure 8 shows fuel flow history as control input. Figure 9 shows excess power, core power, SFC, turbine temperature, core pressure ratio, and core airflow time histories.

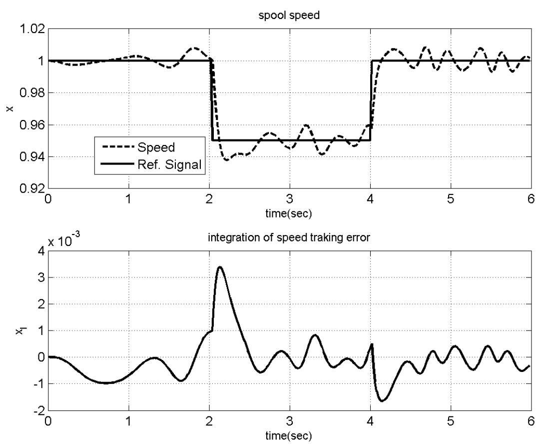


Figure 6. Spool speed and integration of state tracking error histories

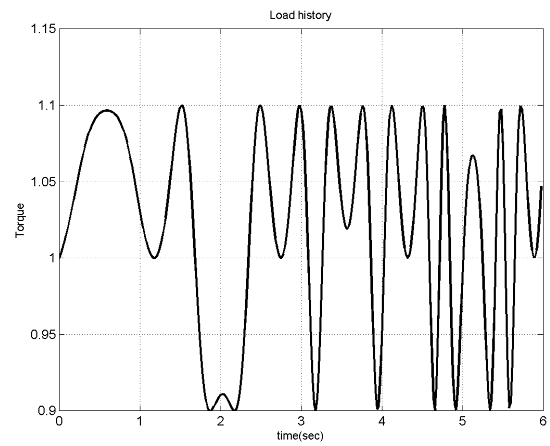


Figure 7. Load history

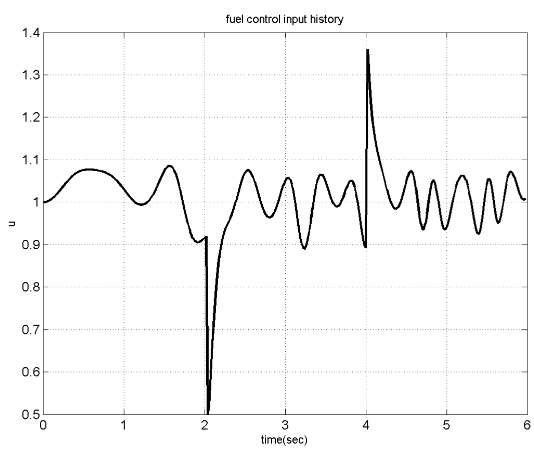


Figure 8. Fuel flow control input history

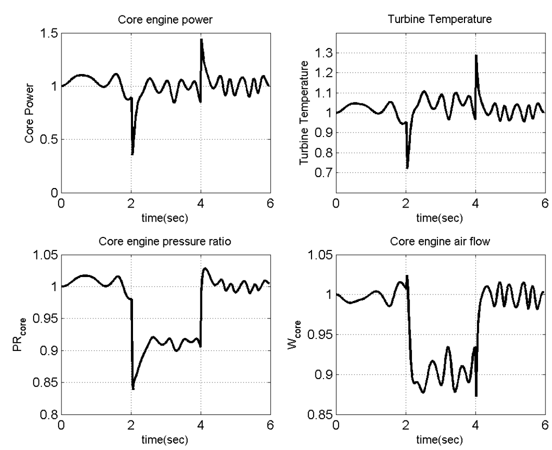


Figure 9. Turbine temperature, SFC, pressure ratio, power and airflow histories

D. Turbofan System Decentralized Linear Control Results

Here we show the results of the simulation for the decentralized case with two different linear controllers to control two different subsystems of the turbofan engine (i.e. engine core and fan). Fuel flow and fan vane angle are the control inputs.We use step reference signal ($y_c(t)$) for the output thrust to track. $r_c(t)$ will be constructed using $y_c(t)$ and $\delta u_3(t)$. The decentralized control structure that we use in this section is shown in figure 5.

The control parameters and initial conditions for all of these cases are

$$
\begin{gathered}
k_{pf} = 9, \quad k_{if} = 75, \quad k_{ia} = -10, \\
x(0) = 1.0.
\end{gathered}
\tag{32}
$$

In this simulation $y_c(t)$ is a step signal which defines the reference spool speed to change from 1 to 0.95. Simulation results are shown in figures 10 to 13. Figure 10 shows the history of the load on core engine, and also estimated, actual and reference thrust time histories. Figure 11 shows spool speed history for nominal and reference plant, and also time histories of integration of the state tracking error and (i.e. x_I) output tracking error (i.e. y_I). The state follows the reference trajectory closely. Figure 12 shows fuel flow, vane angle and exit area histories as control inputs. Figure 13 shows excess power, core power, SFC, turbine temperature, core pressure ratio, fan pressure ratio, core airflow and fan airflow time histories.

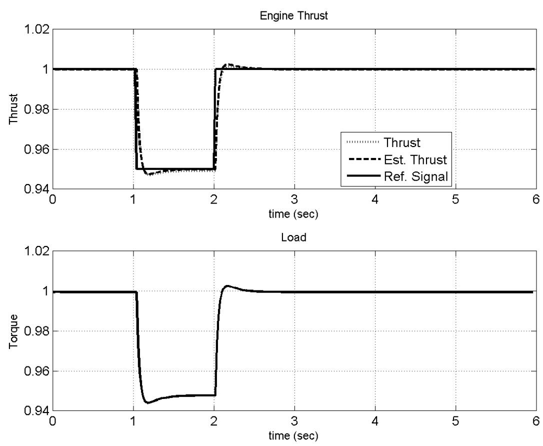


Figure 10. Plant actual thrust, estimated thrust, reference thrust, and load histories

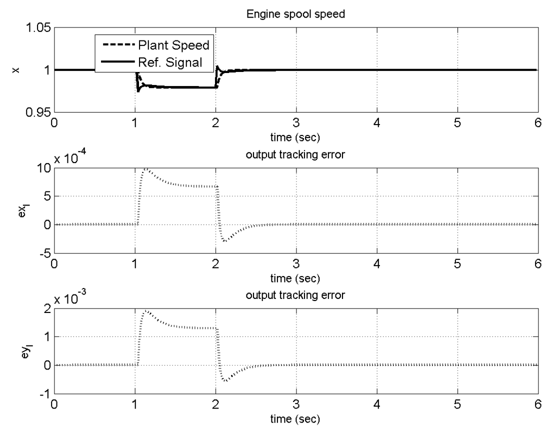


Figure 11. Spool speed, and integration of the state and the output tracking errors histories

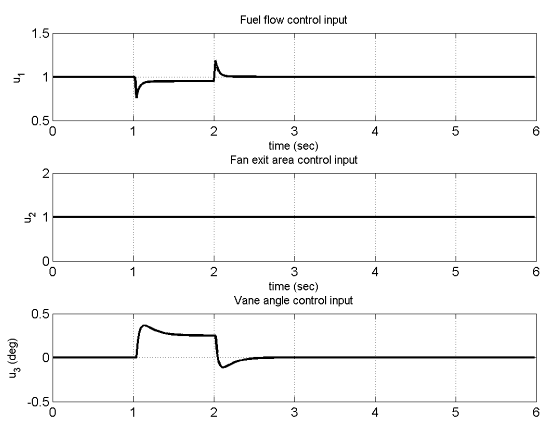


Figure 12. Fuel flow, fan exit area and fan vane angle control inputs histories

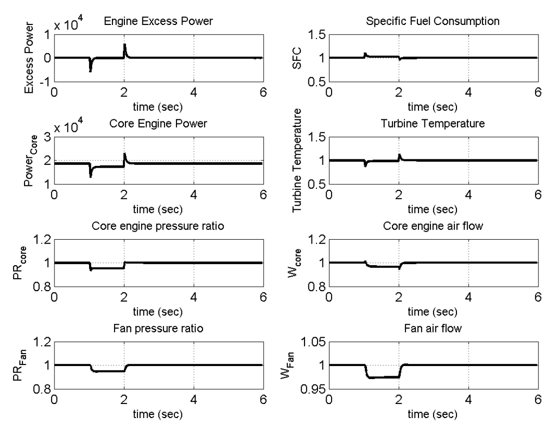


Figure 13. Power, turbine temperature, SFC, fan and core pressure ratio and airflow histories

IV. Distributed Adaptive Control

Since engine dynamics have both parametric and dynamic uncertainties, we decided to use adaptive control technique to control the engine. The basic idea in adaptive control is to estimate the unknown parameters on-line based on measured system signals, and use the estimated parameters in the control input computations. Since adaptive control systems are inherently nonlinear, most of the times, their design and analysis is strongly connected with Lyapunov stability theory.

In this section we develop a distributed (decentralized) control strategy for a turbofan engine using model reference adaptive control (MRAC) technique. The controller design methodology is mostly based on the results developed in references.[9,10]

A model-reference adaptive control (MRAC) system is composed of four parts: a system containing unknown parameters, a reference model for specifying the desired output of the control system, a feedback control law containing adjustable parameters, and an adaptation mechanism for updating the adjustable parameters.

The adaptation mechanism is used to adjust the parameters in the control law. The objective of the adaptation is to make the tracking error converge to zero. The difference from conventional control lies in the structure of this mechanism. The main issue is to synthesize an adaptation mechanism which will guarantee that the control system remains stable and the tracking error converges to zero as the parameters are varied. Adaptation law is not necessarily uniquely defined.

Absence of stability margin metrics and lack of solid theoretical results on distributed adaptive systems with communication constraints (i.e. delay, packet drop, etc) are the key areas to be developed in distributed adaptive control systems.

In the case of stability margins we can implement the methods developed by C. Cao and N. Hovakimyan[11–14] which present adaptive control architecture that adapts fast and ensures uniformly bounded transient response for systems both signals, input and output, simultaneously. This architecture has a low-pass filter in the feedback loop and relies on the small-gain theorem for the proof of asymptotic stability. The tools from these papers can be used to develop a theoretically justified verification and validation framework for adaptive systems.

In case of the distributed adaptive systems with delay we can again use the results developed by C. Cao and N. Hovakimyan[15,16] which extend the results from their previous paper[11] for characterization of the time-delay margin of closed loop systems.

A. Controller Design Strategy

The decentralized adaptive control structure for the turbofan engine model is shown in figure 14. The signals are shown with solid lines and the mechanical interconnection is shown with a dashed line.

1. *Subsystem II: Core Engine Control Design*

The control objective for subsystem II is to design an adaptive controller to achieve tracking $x(t) \to x_m(t)$ as $t \to \infty$.

Here we introduce the integral error in spool speed as an additional state into the system dynamics and write

$$\tilde{x}(t) = \delta x_1(t) - r_c(t), \quad \tilde{x}(0) = 0. \tag{33}$$

The new state will be

$$\delta x_2(t) = x_I(t) = \int_0^t \tilde{x}(\tau) d\tau. \tag{34}$$

The model which we use to control the engine spool speed is developed assuming $\delta u_2(t) = \delta u_3(t) = 0$

$$\begin{aligned} \delta \dot{x}_1(t) &= a.\delta x_1(t) + b_1.\delta u_1(t), \quad \delta x_1(0) = \delta x_2(0) = 0, \\ \delta \dot{x}_2(t) &= \delta x_1(t) - r_c, \end{aligned} \tag{35}$$

where $\delta x_1(t)$ is the spool speed and $\delta x_2(t)$ is the integration of spool speed tracking error.

Let $X(t) = [\delta x_1(t),\ \delta x_2(t)]^T$. The system dynamics (51) can be written as

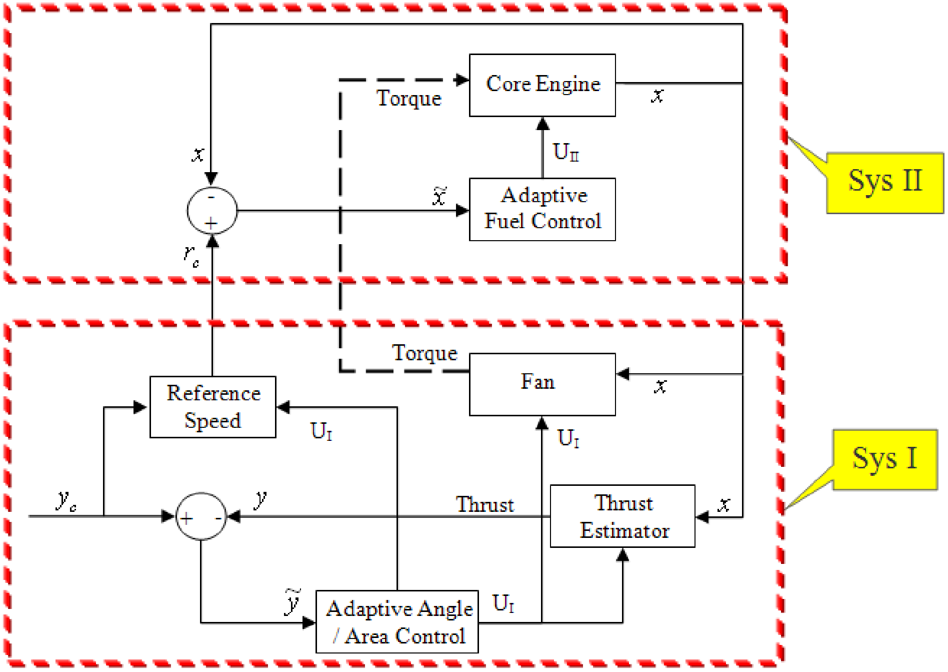


Figure 14. Decentralized adaptive control structure for turbofan engine

$$\begin{bmatrix} \delta\dot{x}_1(t) \\ \delta\dot{x}_2(t) \end{bmatrix} = \underbrace{\begin{bmatrix} a & 0 \\ 1 & 0 \end{bmatrix}}_{\bar{\mathrm{A}}} \underbrace{\begin{bmatrix} \delta x_1(t) \\ \delta x_2(t) \end{bmatrix}}_{\mathrm{X(t)}} + \underbrace{\begin{bmatrix} b_1 \\ 0 \end{bmatrix}}_{\bar{\mathrm{b}}} u_1(t) + \begin{bmatrix} 0 \\ -1 \end{bmatrix} r_c(t). \tag{36}$$

Let the PI controller be given by

$$u_{1lin}(t) = -K_f^T X(t), \tag{37}$$

where $K_f(t) = [k_{pf},\ k_{if}]^T$.

The resulting closed loop system is the desired reference system for adaptive tracking

$$\begin{bmatrix} \delta\dot{x}_{1m}(t) \\ \delta\dot{x}_{2m}(t) \end{bmatrix} = \underbrace{\left(\begin{bmatrix} a & 0 \\ 1 & 0 \end{bmatrix} - \begin{bmatrix} b_1 \\ 0 \end{bmatrix} K_f^T \right)}_{\bar{\mathrm{A}}_{\mathrm{m}}} \begin{bmatrix} \delta x_{1m}(t) \\ \delta x_{2m}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \end{bmatrix} r_c(t), \tag{38}$$

where $\bar{A}_m$ is Hurwitz. The total control input for subsystem II is formed as

$$U_{II}(t) = u_{1lin}(t) + u_{1ad}(t), \tag{39}$$

where $U_{II}(t) = u_1(t)$.

Let $e(t) = X(t) - X_m(t)$ be the tracking error signal. The tracking error dynamics can be formed as

$$\dot{e}(t) = \bar{A}_m e(t) + \bar{b}(\Delta k_f^T(t) X(t)), \quad e(0) = e_0 = 0, \tag{40}$$

where $\Delta K_f(t) = K_f(t) - K_f^*$ denote the parameter errors. K_f^* are ideal values of the adaptation parameters.

The adaptive control can be designed as follows:

$$u_{1ad}(t) = K_f^T(t) X(t), \tag{41}$$

with the following adaptation law:

$$\dot{K}_f(t) = -\Gamma_f X(t)e^T(t)P\bar{b}, \quad K_f(0) = K_{f0}, \tag{42}$$

where $\Gamma_f = \Gamma_f^T > 0$ is the matrix of the adaptation gains.

Defining the following Lyapunov function candidate

$$V(e(t), \Delta K_f(t)) = e^T(t)Pe(t) + \Delta K_f^T(t), \Gamma_x^{-1}\Delta K_f(t), \tag{43}$$

where $P = P^T > 0$ solves the algebraic Lyapunov equation

$$\bar{A}_m^T P + P\bar{A}_m = -Q, \tag{44}$$

for arbitrary $Q > 0$. The time derivative of the Lyapunov function (43) along trajectories (52), (54) is

$$\dot{V}(t) = -e^T(t)Pe(t) \leq 0. \tag{45}$$

Hence the derivative of the Lyapunov function is negative semidefinite, therefore all signals are bounded. The application of Barbalat's lemma implies asymptotic convergence of tracking error to zero.

2. Subsystem I: Fan Control Design

The goal of the control in this section is to force the output to track a desired command. Output is the estimation of thrust as a linear function of the plant state. The controller in this section is a combination of a nominal I (Integral) controller and an adaptive controller. The integral controller is used to decrease the steady state error, and also to generate a reference model for adaptive controller.

We design a full state feedback adaptive controller so that $y(t)$ tracks a given smooth trajectory $y_c(t)$, while all other signals remain bounded.

Here we introduce the integral error of output as an additional state into the system dynamics and write

$$\tilde{y}(t) = y(t) - y_c(t) = c.\delta x(t) + d_3.\delta u_3(t) - y_c(t). \tag{46}$$

The new state will be

$$y_I(t) = \int_0^t \tilde{y}(\tau)d\tau. \tag{47}$$

Then we have

$$\delta\dot{x}_3(t) = y(t) - y_c(t) = c.\delta x_1(t) + d_3.\delta u_3(t) - y_c(t), \quad \delta x_3(0) = 0, \tag{48}$$

where $\delta x_3(t)$ is the integration of output thrust tracking error.

The total control input for subsystem I is formed as

$$U_I(t) = u_{lin}(t) + u_{ad}(t), \tag{49}$$

where $U_I(t) = b_2u_2(t) + b_3u_3(t)$.

Let the integral controller be given by

$$u_{lin}(t) = -k_{ia}\delta x_3(t). \tag{50}$$

Then the reference model will be

$$\delta\dot{x}_{3m}(t) = c.\delta x_{1m}(t) + d_3.(k_{ia}\delta x_3(t)) - y_c(t), \quad \delta x_{3m}(0) = 0. \tag{51}$$

Let $e_3(t) = \delta x_3(t) - \delta x_{3m}(t)$ be the tracking error signal. The tracking error dynamics can be formed as

$$\dot{e}_3(t) = c.e_1(t) + d_3.k_{ia}e_3(t) + d_3.\Delta k_a(t)\delta x_3(t), \quad e(0) = e_0 = 0, \tag{52}$$

where $\Delta k_a(t) = k_a(t) - k_a^*$. k_a^* is the ideal value of the adaptation parameter.

The adaptive control can be designed as follows:

$$u_{ad}(t) = k_a(t)\delta x_3(t), \tag{53}$$

with the following adaptation law:

$$\dot{k}_a(t) = -\gamma_a \delta x_3(t) e_3(t) sign(d_3), \quad k_a(0) = k_{a0}, \tag{54}$$

where $\gamma_a > 0$ is the adaptation gain.

Lyapunov function candidate and stability analysis for this controller is similar to the previous controller. The stability analysis is done only for each subsystem. The complete stability analysis for the decentralized interconnected system is not done here.

B. Core Engine Adaptive Control Results

The control objective is to design a robust adaptive control such that the state of the nominal system tracks a smooth trajectory. The linearized nominal system for this simulation is $\dot{x}(t) = a.\delta x(t) + b.\delta u_1(t) = -1.8\delta x(t) + 1.7460\delta u_1(t)$. In this simulation we assumed that torque is a function of time and defined it as $T(t) = 1 + 0.1\sin(1.3(1 + \sin(4t))t)$. State tracking error is defined as $e(t) = x(t) - x_m(t)$.

The control parameters and initial conditions are

$$K_f = \begin{bmatrix} 9 \\ 75 \end{bmatrix}, \ \Gamma_x = \begin{bmatrix} 5 & 0 \\ 0 & 30 \end{bmatrix}, \ Q = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}, \ P = \begin{bmatrix} 6.5133 & -1.0000 \\ -1.0000 & 0.2035 \end{bmatrix}, \quad K_f(0) = \begin{bmatrix} -9 \\ -75 \end{bmatrix}. \tag{55}$$

In this simulation $r_c(t)$ is a step signal which defines the reference spool speed to change from 1 to 0.95. Simulation results are shown in figures 15 to 18. Figure 15 shows spool speed history for nominal and reference plant and also state tracking error history. It can be seen that state follows the reference trajectory very closely. Figure 16 shows fuel flow history as control input. Figure 17 shows the history of the two adaptation parameters used in the adaptive control design. Figure 18 shows excess power, core power, SFC, turbine temperature, core pressure ratio, and core airflow time histories.

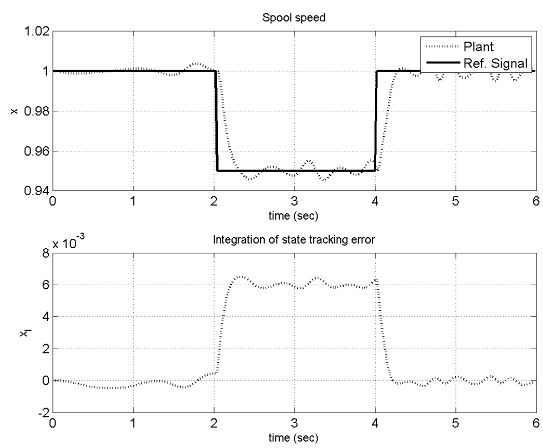


Figure 15. Spool speed and state tracking error histories

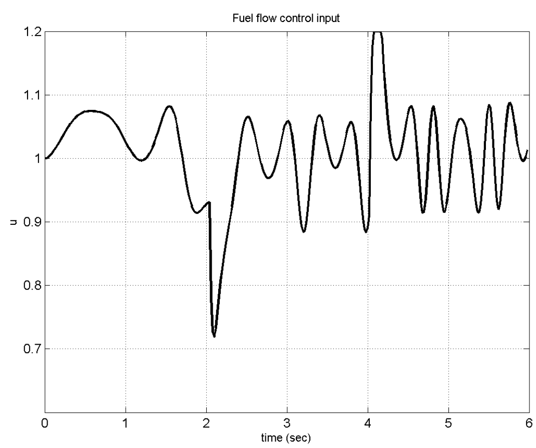


Figure 16. Fuel flow control input history

In figure 6, a simulation of a step change in reference speed from 100 to 95 percent is shown for the engine core being controlled by the linear PI controller used to define the adaptive reference model. The controller is attempting to maintain the references speed under the influences of a varying torque input. Figure 15 shows the same simulation for the adaptive controller, using the same time trace of disturbance torque. In both cases, the controllers follow the reference rather quickly, but the adaptive controller exhibits a smaller amount of variation due to the disturbance torque. The controller is able to adapt to changes in the linearization caused by nonlinear characteristics of the engine as it moves away from the design condition. This is highlights one of the key reasons for the choice of an adaptive control structure in the distributed architecture design.

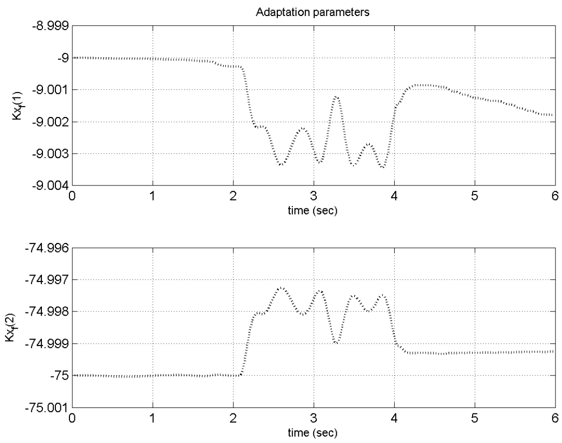


Figure 17. Adaptation parameters histories

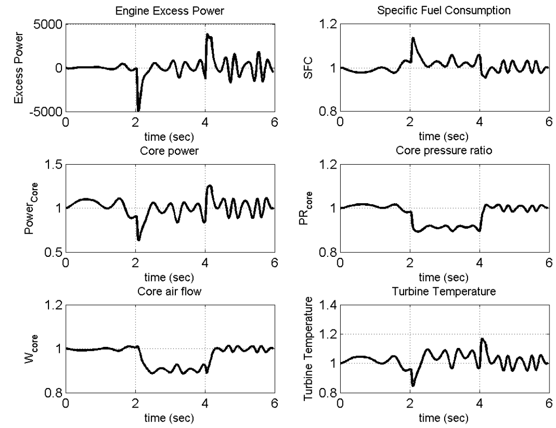


Figure 18. Turbine temperature, SFC, pressure ratio, power and airflow histories

C. Turbofan System Decentralized Adaptive Control Results

Adaptive decentralized turbofan engine control using fuel flow and fan vane angle is done in this section. The decentralized structure has two control loops, one for the fan subsystem and the other one for the core engine. For fan subsystem we let the fan exit area to be constant and equal to its design value (i.e. $u_2(t) = 1$); hence, the vane angle is the main control input. We measure the spool speed and estimate the thrust and use these two values to design an adaptive controller which actuates fan vanes angle. The main goal for this loop is to force the thrust as the output to track a desired trajectory. For the core engine subsystem the input is fuel flow.

The control parameters and initial values for subsystem II are

$$K_f = \begin{bmatrix} 9 \\ 75 \end{bmatrix}, \; \Gamma_x = \begin{bmatrix} 5 & 0 \\ 0 & 30 \end{bmatrix}, \; Q = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}, \; P = \begin{bmatrix} 6.5133 & -1.0000 \\ -1.0000 & 0.2035 \end{bmatrix}, \quad K_f(0) = \begin{bmatrix} -9 \\ -75 \end{bmatrix}. \tag{56}$$

The plant initial conditions are $x(0) = x_m(0) = 1.00$. The control parameters and initial values for subsystem I are

$$k_{ia} = -10, \; \gamma_a = 10, \; k_a(0) = 10. \tag{57}$$

In this simulation $y_c(t)$ is a step signal which defines the reference thrust to change from 1 to 0.95. Simulation results are shown in figures 19 to 23. Figure 19 shows the history of the load on the core engine, and also actual, estimated and reference,thrust time histories. As it is apparent actual and estimated thrust both follow reference signal closely. Figure 20 shows spool speed history for nominal and reference plant, and also time history of integration of the output tracking error (i.e. y_I). State follows the reference trajectory closely. Figure 21 shows fuel flow, vane angle and exit area histories as control inputs. Figure 22 shows the history of the adaptation parameters for the two adaptive controllers for subsystems I and II. The adaptation parameters converge to their steady state values fast enough. Figure 23 shows excess power, core power, SFC, turbine temperature, core pressure ratio, fan pressure ratio, core airflow and fan airflow time histories.

The simulations indicate that the decentralized adaptive controller appears to be operating properly, although no formal stability proof is currently available.

Figures 10 and 19 show the simulations of the complete distributed control system using both the linear controllers, from which the reference models are based, as well as the full adaptive controllers. The figure shows a step change in requested thrust from 100 to 95 percent. No disturbance inputs have been added to the simulation. The simulation shows accurate thrust tracking under both techniques, with the adaptive control excelling in overshoot prevention. As seen with the core controller alone, the adaptive controller shows increased robustness to variations in the model caused by nonlinearities away from the design point. This robustness to model variation shows promise to improving performance the various issues that may arise in a non-ideal distributed environment, such as communication interruption or delay.

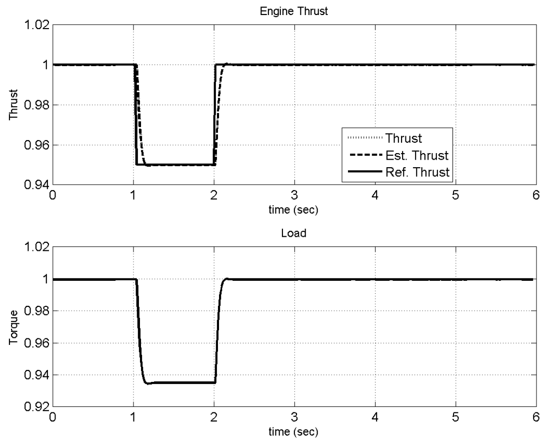


Figure 19. Plant actual thrust, estimated thrust, reference thrust, and load histories

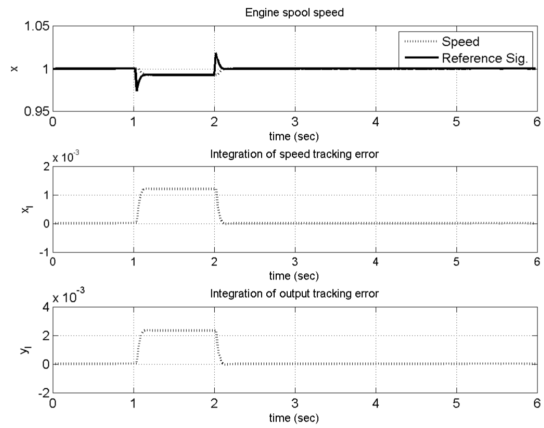


Figure 20. Spool speed and reference trajectory histories

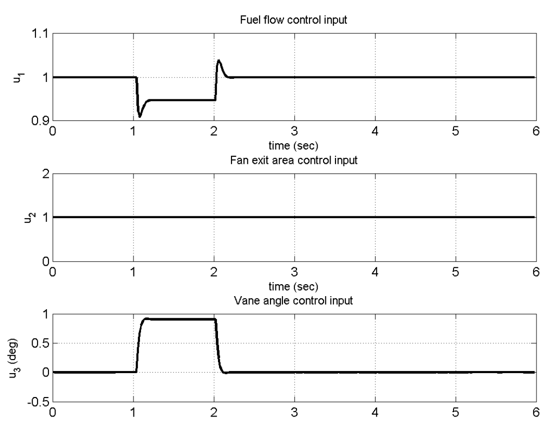


Figure 21. Fuel flow, vane angle and exit area control input histories

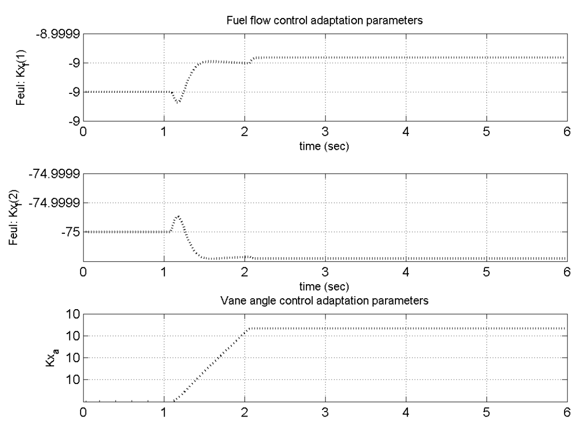


Figure 22. Adaptation parameters histories for two controllers of System I and II

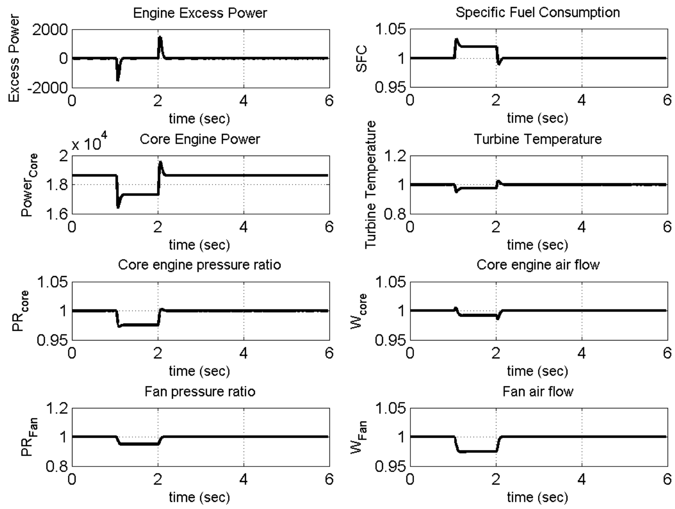


Figure 23. Power, turbine temperature, SFC, fan and core pressure ratio and airflow histories

V. Conclusion

For distributed control purpose we developed a simplified dynamic model of a generic turboshaft engine driving a lift fan. Core and fan subsystems are defined as the subsystems which we intend to control using a spatially distributed control system. In this distributed model fuel flow is the control input for the core subsystem, and vane angle is the control input for the fan subsystem. For this model we developed a distributed linear control structure. Afterwards we used the linear controllers to construct desired reference models for our decentralized adaptive controller. The simulations show accurate spool speed tracking and thrust tracking under both linear and adaptive techniques, with the adaptive control excelling in overshoot prevention with less oscillation in tracking. The current competitors to Distributed Adaptive Engine control are the traditional FADEC scheme and simple distributed control. Both Distributed Adaptive Engine Control and simple distributed control offer a substantial improvement in the cost, weight, and modularity over the traditional FADEC approach. Distributed Adaptive control has additional benefits in system reliability, controller stability, and modularity of the entire engine system that give it a significant advantage over any simple distributed controller currently under development. In future, we will investigate the effect of networked control system issues such as network induced delay and packet drop on the stability and performance of the developed distributed control structure for turbofan systems.

VI. Acknowledgments

This material is based upon work supported by the Air Force Research Laboratory (AFRL) under Contract No FA9550-08-C-0061.

References

[1]Behbahani, A., Culley, D., Smith, B. J., and *et. al.*, "Status Vision and Challenges of an Intelligent Distributed Engine Control Architecture," *Proceedings of SAE AeroTech Congress and Exhibition*, SAE 2007-01-3859, Los Angeles, CA, 2007.

[2]Culley, D. and Behbahani, A., "Communication Needs Assessment for Distributed Turbine Engine Control," *Proceedings of the 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA-2008-5281, Hartford, CT, 2008.

[3]Culley, D. and Saus, T. R., "Concepts for Distributed Engine Control," *Proceedings of the 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA-2007-5709, Cincinnati, OH, 2007.

[4]Epstein, A., An Engineering History of Gas Turbines, Lecture 1 / 16.511-Aircraft Turbine Engines, unpublished, 2007.

[5]Cumpsty, N., *Jet Propulsion*, Cambridge University Press, 2003.

[6]http://www.cfm56.com/company/work-split, Jan. 2009.

[7]Kerrebrock, J. L., *Aircraft Engines and Gas Turbines*, The MIT Press, Cambridge, 1996.

[8]Cohen, H., Rogers, G. F. C., and Saravanamuttoo, H. I. H., *Gas Turbine Theory*, Prentice Hall, Harlow, 2001.

[9]Hovakimyan, N., *Robust Adaptive Control Course Notes*, University of Illinois at Urbana Champaign (UIUC), 2009.

[10]Loannou, P. and Sun, J., *Robust Adaptive Control*, Prentice Hall, 1996.

[11]Cao, C. and Hovakimyan, N., "Design and Analysis of a Novel L_1 Adaptive Control Architecture with Guaranteed Transient Performance," *IEEE Transactions on Automatic Control*, Vol. 53, No. 2, 2008.

[12]Cao, C. and Hovakimyan, N., "Novel L_1 Neural Network Adaptive Control Architecture With Guaranteed Transient Performance," *IEEE Transactions on Neural Networks*, Vol. 18, No. 4, 2007.

[13]Cao, C. and Hovakimyan, N., "Design and Analysis of a Novel L_1 Adaptive Controller, Part I: Control Signal and Asymptotic Stability," *Proceedings of the 2006 American Control Conference*, IEEE, Minneapolis, Minnesota, 2006.

[14]Cao, C. and Hovakimyan, N., "Design and Analysis of a Novel L_1 Adaptive Controller, Part II: Guaranteed Transient Performance," *Proceedings of the 2006 American Control Conference*, IEEE, Minneapolis, Minnesota, 2006.

[15]Cao, C. and Hovakimyan, N., "Guaranteed transient performance with L_1 adaptive controller for systems with unknown time-varying parameters and bounded disturbances: Part I," *Proceedings of the 2007 American Control Conference*, IEEE, New York, 2007.

[16]Cao, C. and Hovakimyan, N., "Stability Margins of L_1 Adaptive Controller: Part II," *Proceedings of the 2007 American Control Conference*, IEEE, New York, 2007.

Georgia Tech College of Engineering

Aurora FLIGHT SCIENCES

Distributed Control of Turbofan Engines

Mehrdad Pakmehr

Outline

- Overview
- Turbofan Model
- Distributed Control Concepts for Turbofan Systerms
- Distributed Linear Control
  - Core linear control
  - Decentralized linear control architecture
- Distributed Adaptive Control
  - Core adaptive control
  - Decentralized adaptive control architecture
- Summary and Future Work

Overview

Objective / Approach / Goals

- Objective: Research the control-theoretic issues associated with distributed control of non-homogenous systems containing adaptive components. Develop the functional architecture of a distributed control system in a gas turbine application.
- Approach: Georgia Tech will research and assess approaches to distributed control while Aurora identifies applications and builds models. The control schemes developed by Georgia Tech will be assessed on a generic gas turbine engine model coupled with a communication emulator.
- Goals: Demonstrate the stability of a distributed controller in a Gas Turbine and identify potential performance benefits of this new control architecture

Impact of Distributed Engine Control on Future Engines

- Current Engine Control Architecture is Outdated
  - Essentially, FADEC is a fuel controller that has been made digital
  - Complexity has increased with number of sensors/actuators, need for health management, etc.
  - Further advancements are hampered by unfavorable complexity/reliability, cost/benefit ratios
  - A change in overall architecture is needed
- Smart Sensors/Actuators and Smart Components Offer a New Paradigm for Future Engines
  - Dramatic reduction in wiring / complexity
  - Distribution of health management functions to smart elements
  - Component performance improvements
  - Better fault handling
  - Flexibility to incorporate performance-improving component tailoring
  - Modularity of control system and engine components

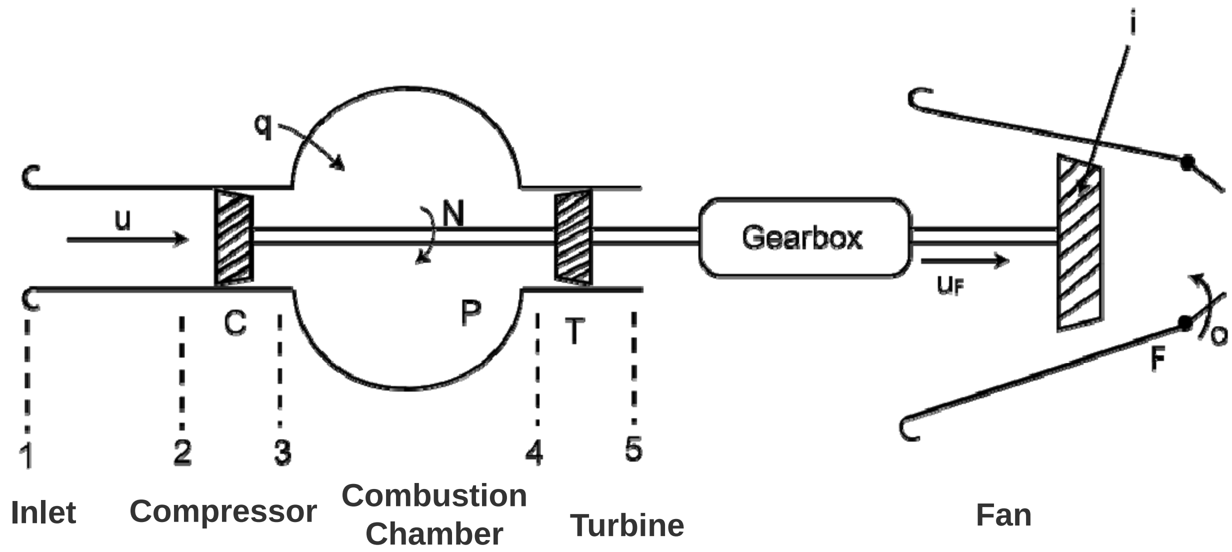
Turbofan Model

Turbofan Model Assumptions and Simplifications

Simplified First-principles based dynamic model used for control law development

- Only the dynamics of the spool are considered.
- The analysis assumes sea level static operation of the engine system, typical of a hovering condition for a VTOL UAV.
- The turbine expands the exhaust gases of the core perfectly to ambient pressure, such that all possible work is extracted from the flow. The exhaust of the core is assumed to have no impact on the thrust produced by the fan.
- Non-ideal efficiencies are assumed for the fan, compressor, combustor, and turbine, but all other components are assumed to operate ideally.
- The core is modeled as a simple gas generator with no secondary or bleed flows for turbine cooling or other uses.
- The mass and temperature of the fuel is ignored in the calculations. The fuel is simply modeled as adding heat to the thermodynamic cycle in accordance with its mass flow rate and heat of combustion.
- The calculations assume that the specific heat of the air going through both the core and the fan is independent of temperature.

Turbofan Model



Inputs:
i: fan blade incidence
o: nozzle position
q: incremental fuel flow

The dynamics of the spool can be described from Newton's second law by the sum of the torques produced by the turbomachinary components (T), as well as the overall rotational inertia of the system (I).

$$I\dot{\omega} = T_t - T_c - T_f$$

t, c, and f represent the turbine, compressor, and fan respectively.

Torque and power for each component determined analytically from thermodynamic and mechanical matching between components

Linearized turbofan model

x(t): state, non-dimensional spool speed
y(t): output, thrust
u_1(t): fuel flow control input
u_2(t): fan exit area control input
u_3(t): fan vane angle control input

$$\dot{x}(t) = f(x(t), u_1(t), u_2(t), u_3(t))$$
$$y(t) = g(x(t), u_2(t), u_3(t))$$

$$\delta x = x - x_{des},\ \delta u = u - u_{des} \qquad x_{des} = 1, u_{des} = [1,\ 1,\ 0]^T \qquad y_{des} = 1$$

$$\delta \dot{x}(t) = a.\delta x(t) + b_1.\delta u_1(t) + b_2.\delta u_2(t) + b_3.\delta u_3(t)$$

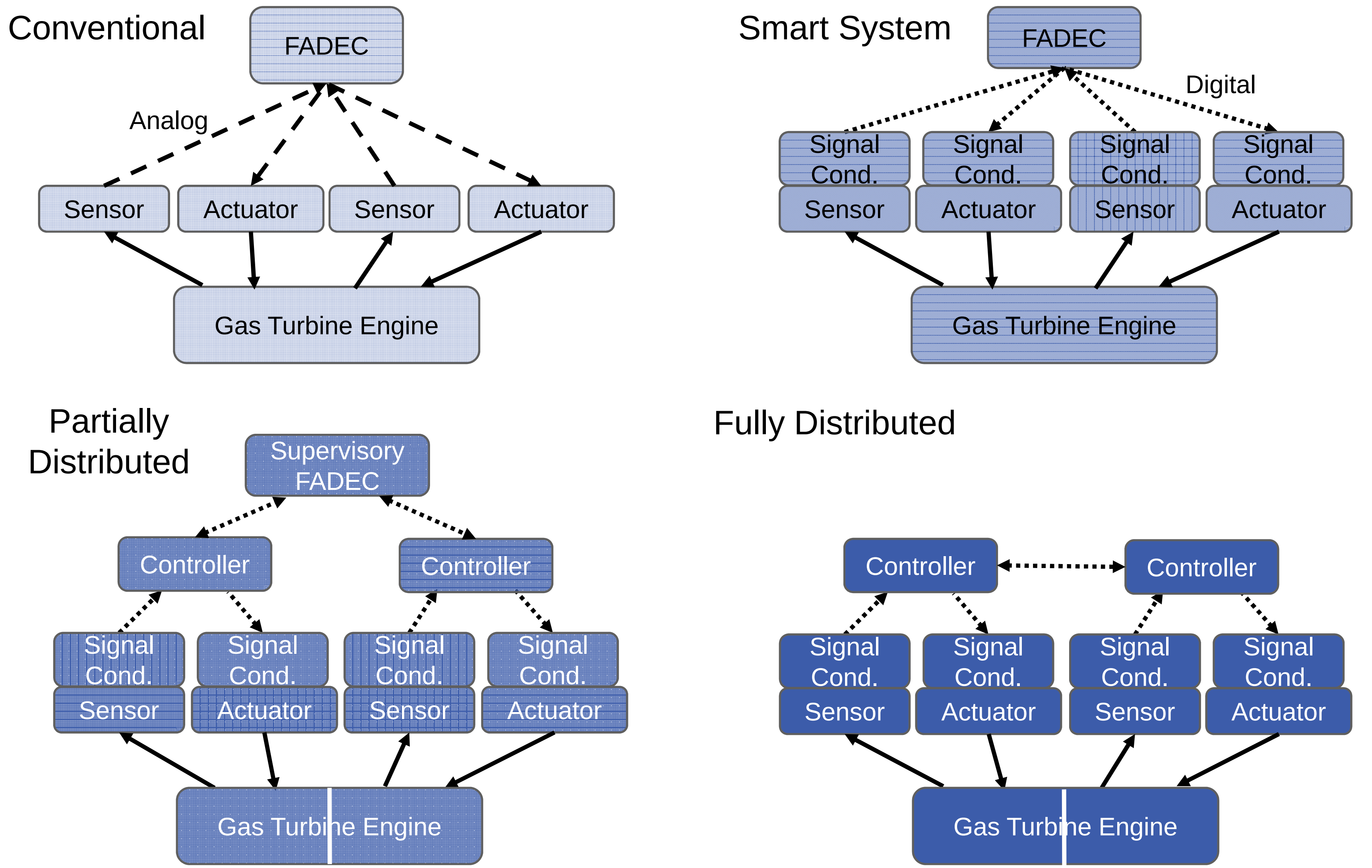
$$\delta y(t) = Thrust = c.\delta x(t) + d_2.\delta u_2(t) + d_3.\delta u_3(t)$$

$$a = -4.63,\ b_1 = 1.78,\ b_2 = 0.31,\ b_3 = 2.96,\ c = 1.921 \quad d_1 = 0,\ d_2 = 0.215,\ d_3 = -1.44$$

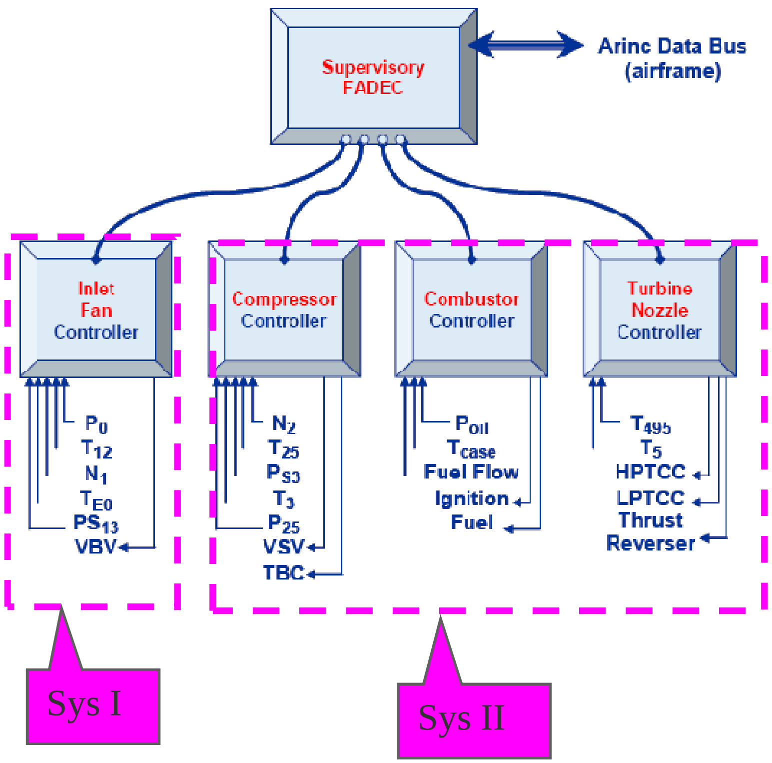
$$u_1(t) \in [0.3,\ 1.2] \qquad u_2(t) \in [0.8,\ 1.2] \qquad u_3(t) \in [-10,\ 10](deg)$$

Distributed Control Concepts for Turbofan Systems

Control Approaches for Gas Turbines



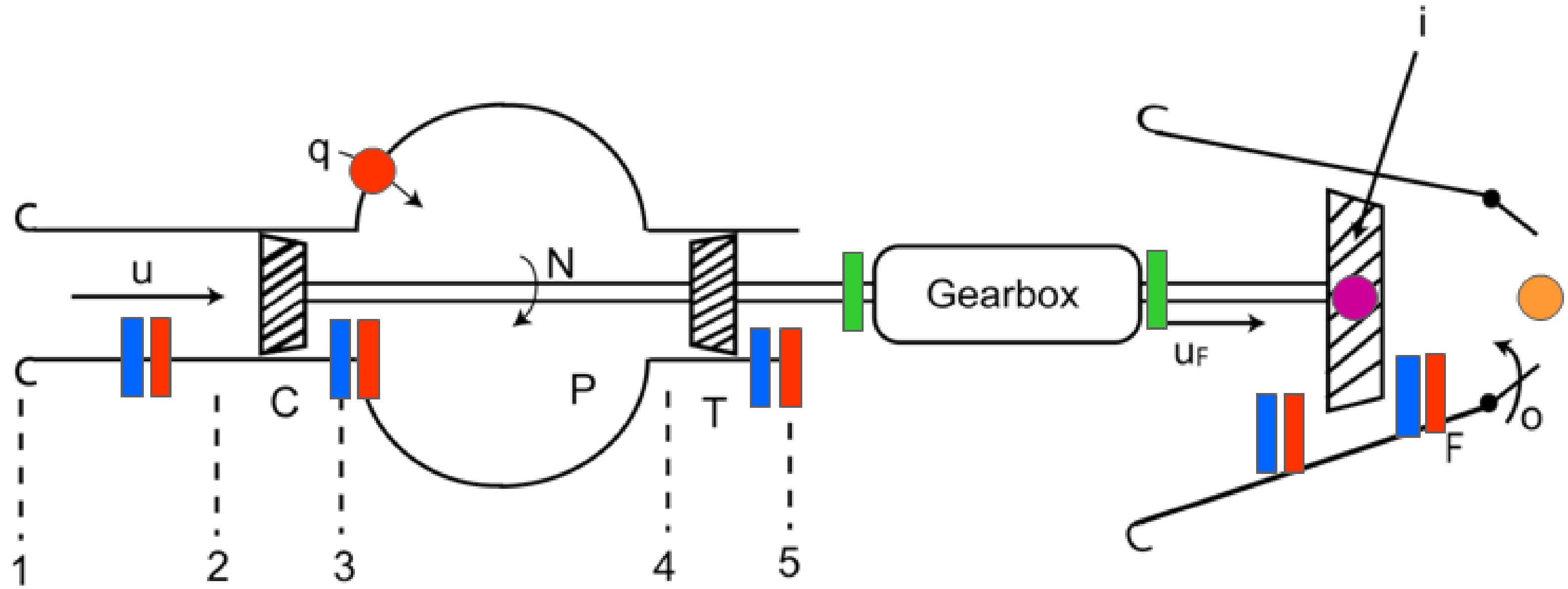
Distributed Control Structure



Ref.: D. Culley and A. Behbahani, *Communication Needs Assessment for Distributed Turbine Engine Control,* AIAA 2008-5281

- The highlighted subsystems are candidates for simplified, distributed control structure.
- In our model, system I is analogous to the “Inlet Fan”, and system II is analogous to other three components (i.e., Compressor, Combustor, Turbine Nozzle).

Possible sensor and actuator locations



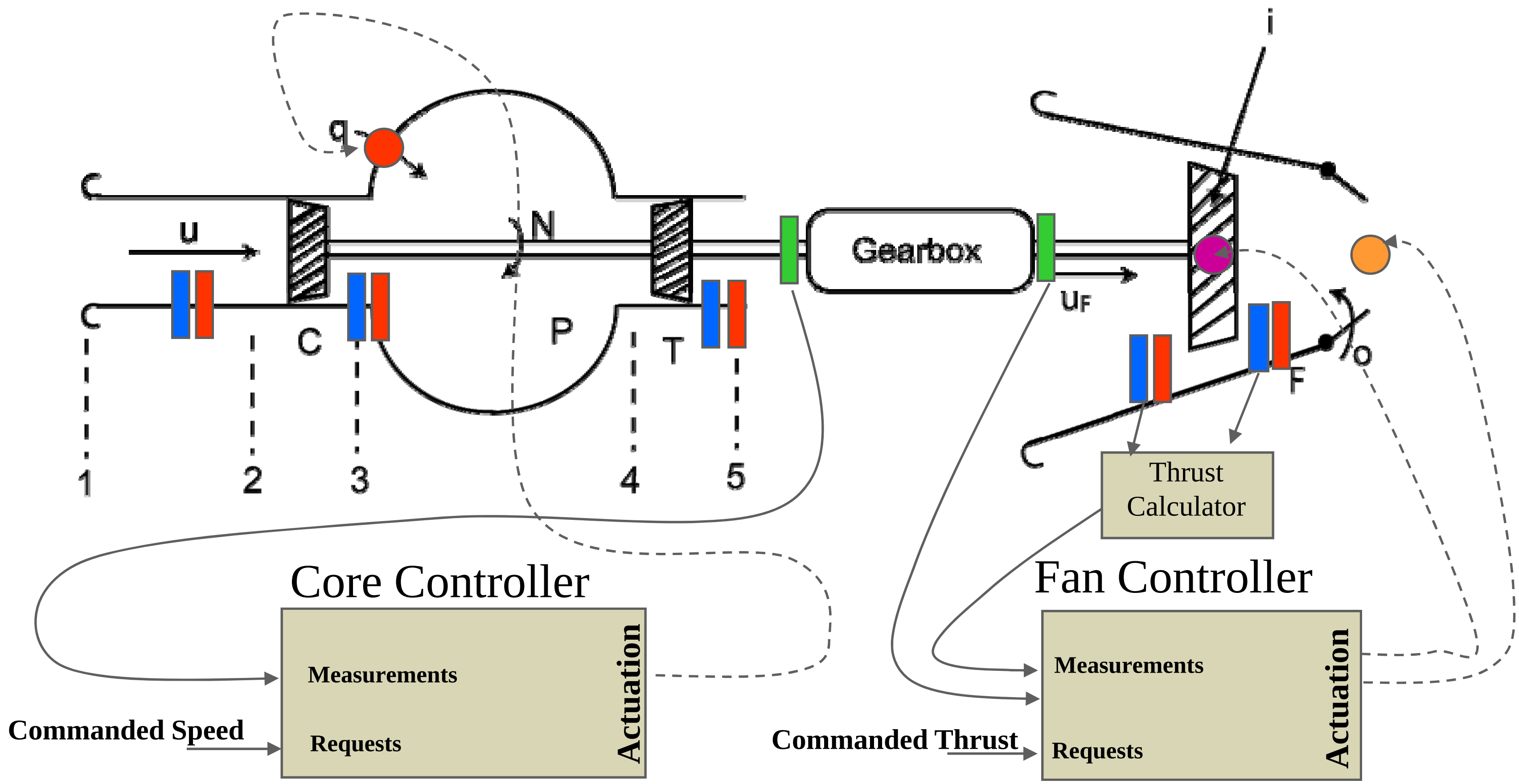
Measurements

- Pressure sensors
- Temperature sensors
- Speed sensors

Control Signals

- Fuel flow actuation
- Vane angle actuation
- Exit area actuation

Example Distributed Control Architecture

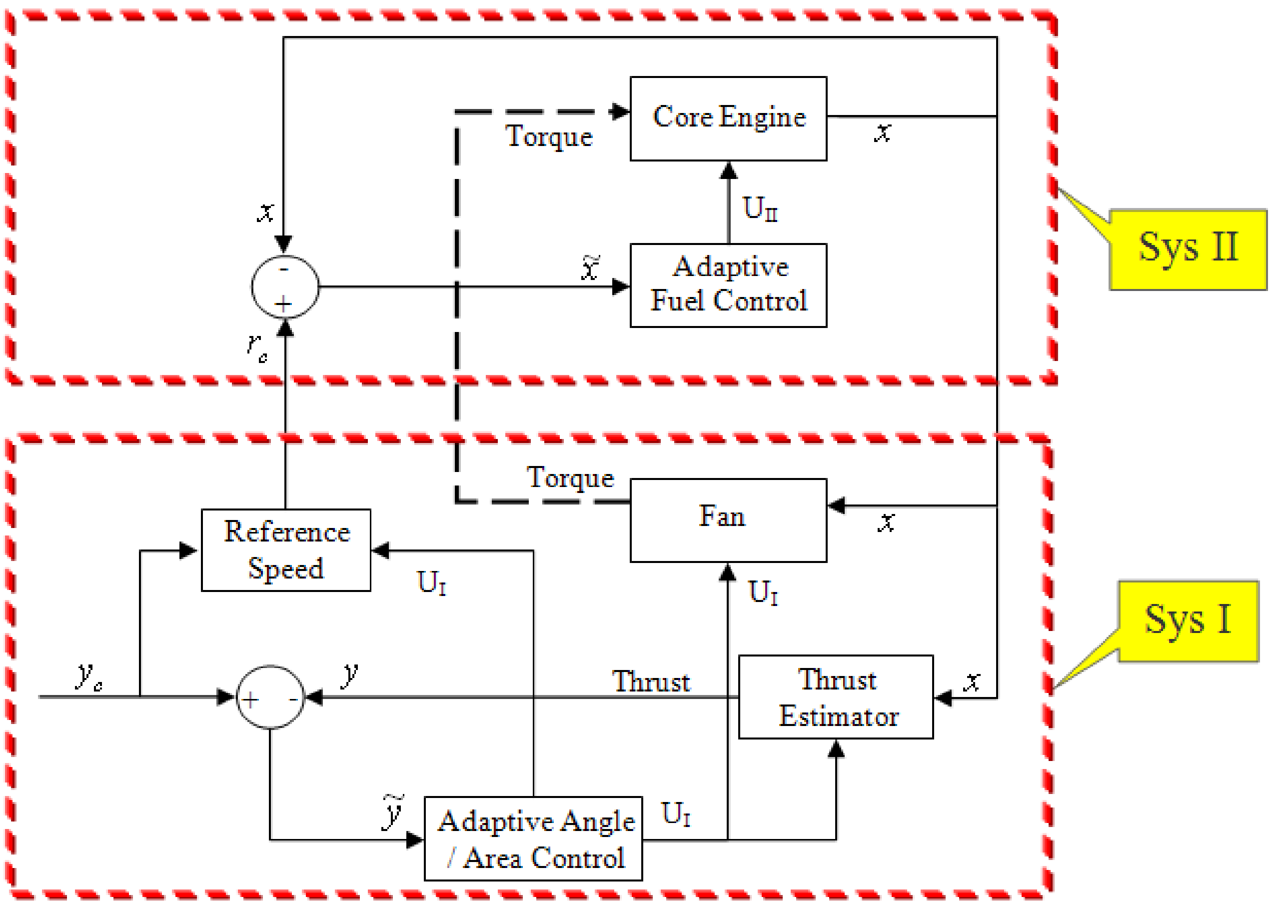


Fuel flow loop closed by speed measurement

Vane and Area loops closed by thrust estimation and speed measurement

Decentralized Linear Controller

Decentralized Linear control structure for turbofan system



x(t): state, spool speed
y(t): output, thrust
$u_{II}(t)$: fuel flow control input
$u_I(t)$: fan vane angle control input

Reference speed: $$r_c(t) = [y_c(t) - y_{des} - d_3(u_3 - u_{3des})(\pi/180)]/c + x_{des}$$

Decentralized Linear Control

System I: Fan Control Design

$$u_3(t) = k_{ia} y_I(t) \qquad \tilde{y}(t) = y(t) - y_c(t) \qquad y_I(t) = \int_0^t \tilde{y}(\tau) d\tau$$

$$k_{ia} < 0$$

Obtain speed reference signal r_c(t) using y_c(t):

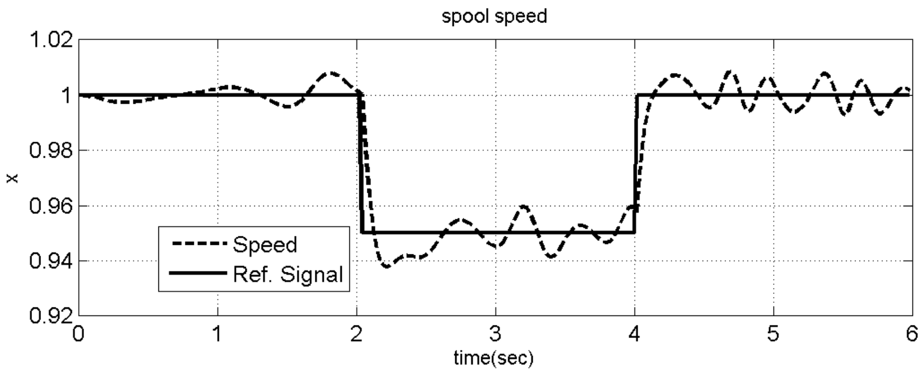
$$r_c(t) = [y_c(t) - y_{des} - d_3(u_3 - u_{3des})(\pi/180)]/c + x_{des}$$

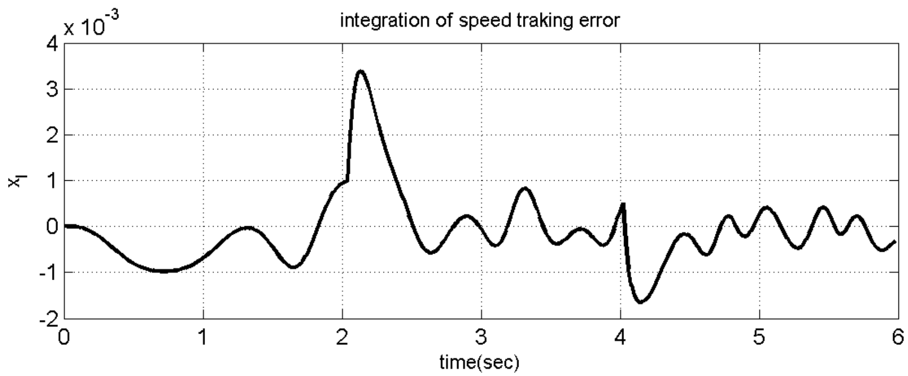
System II: Core Control Design

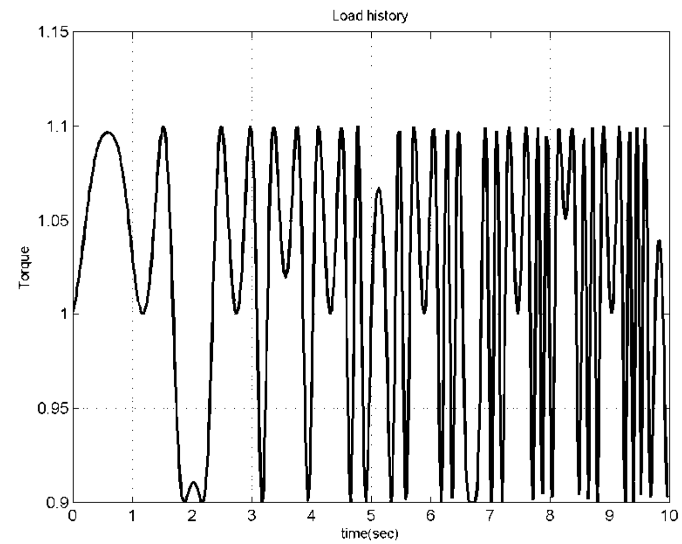
$$u_1(t) = k_{pf}\tilde{x} + k_{if} x_I(t) \qquad \tilde{x}(t) = \delta x_1(t) - r_c(t). \qquad x_I(t) = \int_0^t \tilde{x}(\tau) d\tau$$

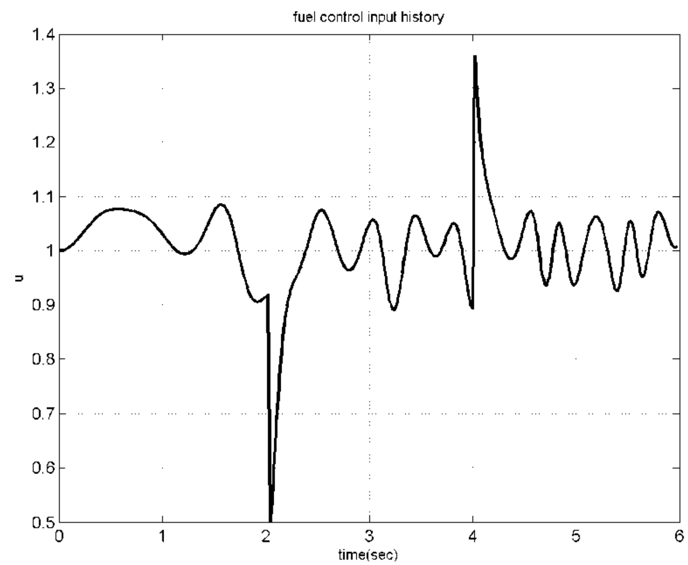
Simulation – Core Linear Control

$$T(t) = 1 + 0.1\sin(1.3(1+\sin(4t))t)$$

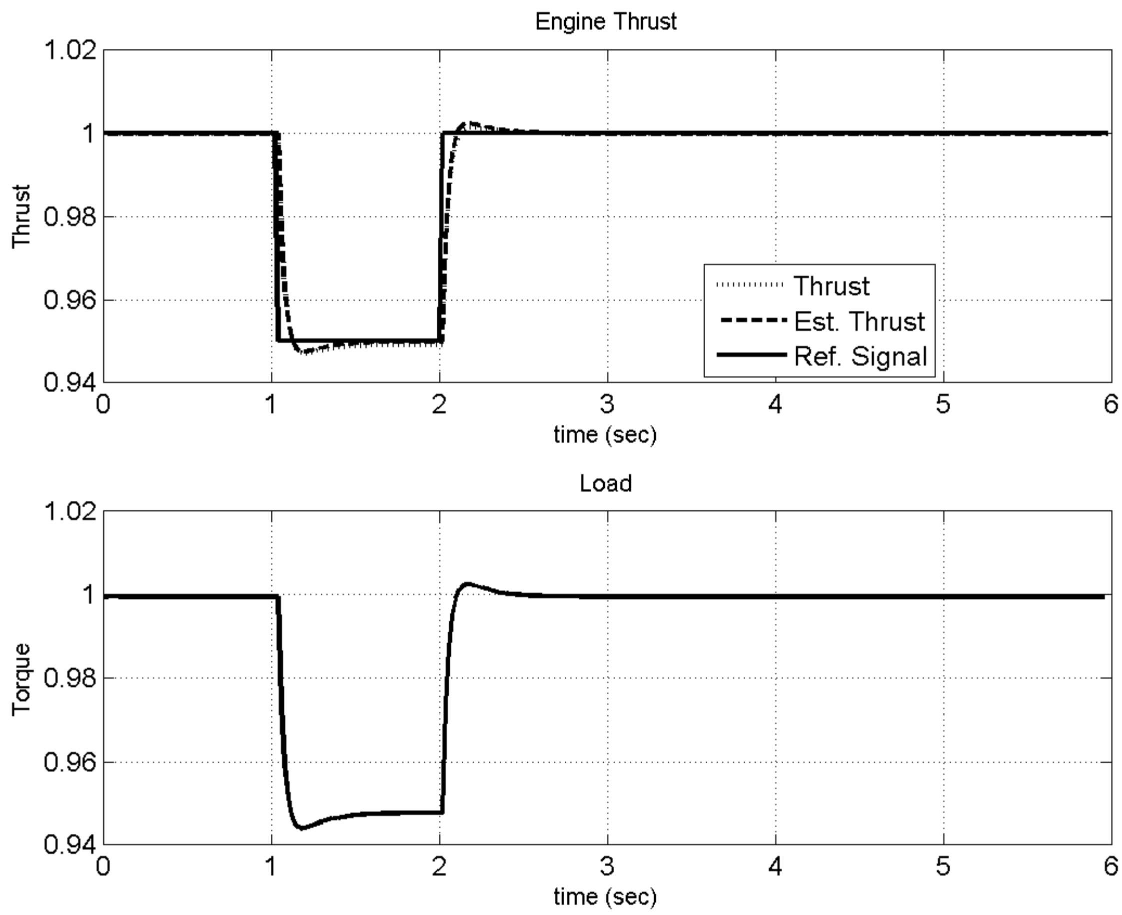




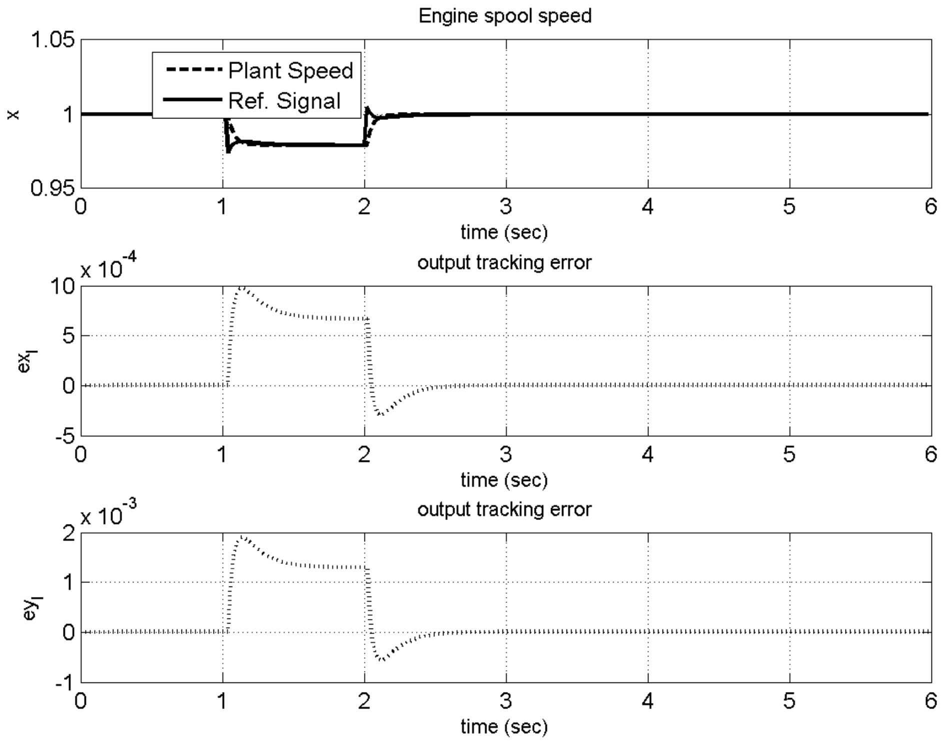


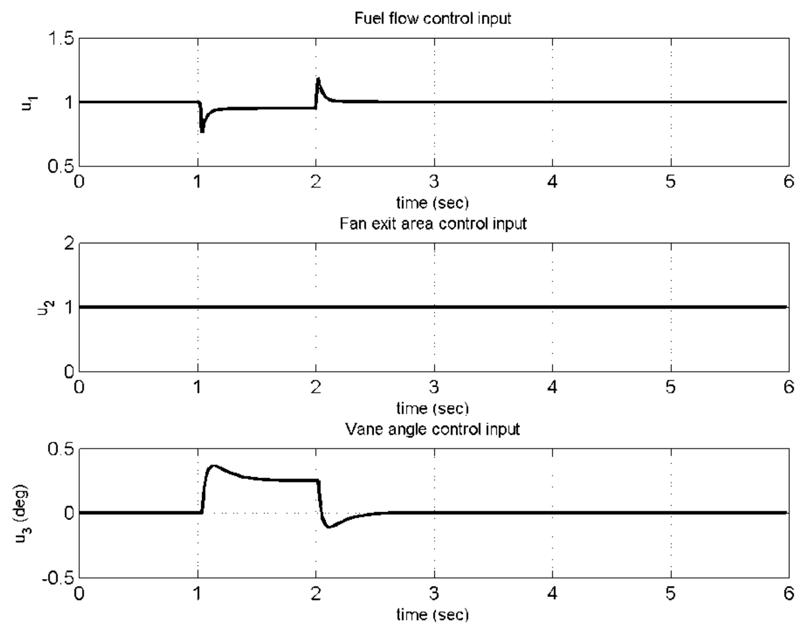


Simulation – Decentralized Linear Control

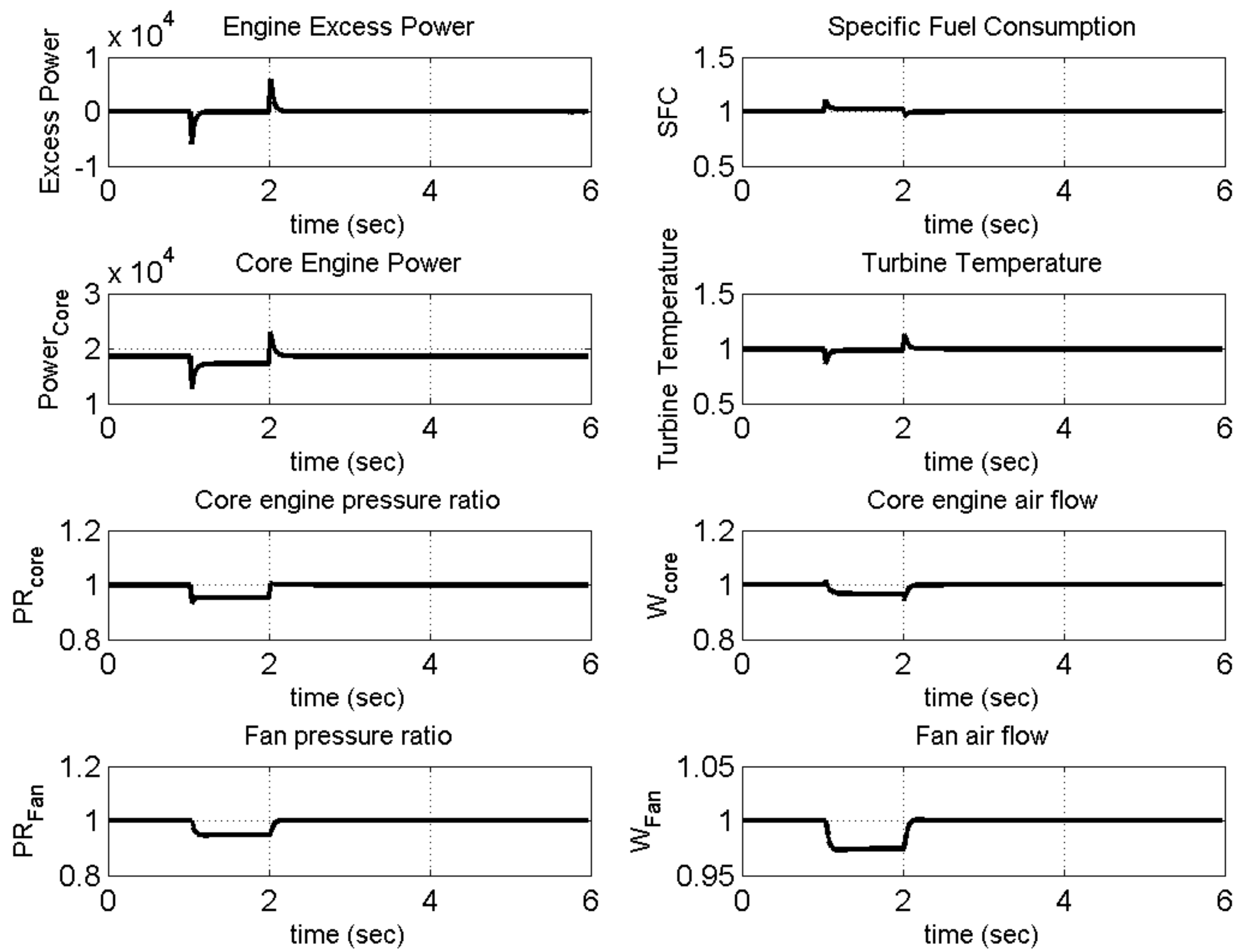


Simulation – Decentralized Linear Control (Cont.)



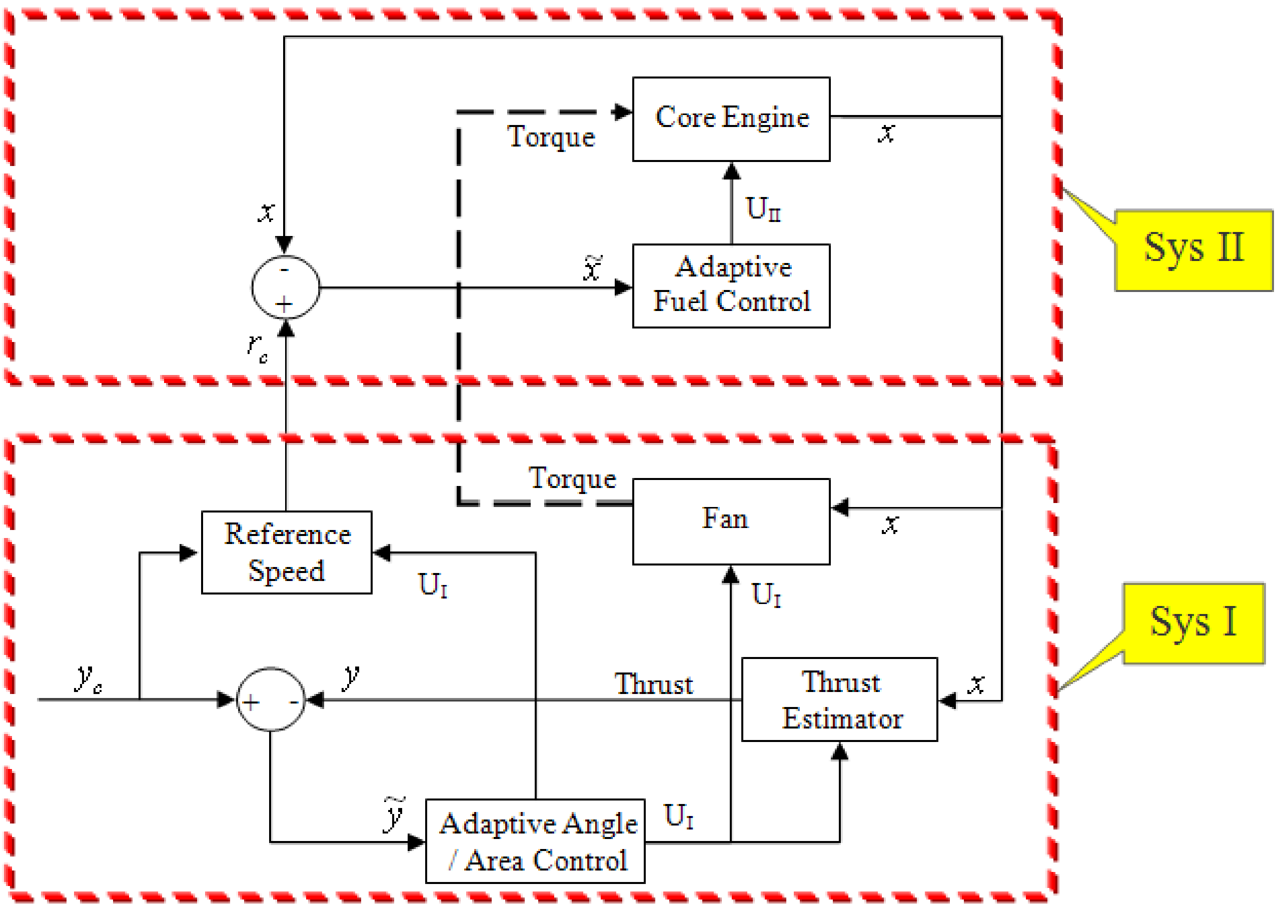


Simulation – Decentralized Linear Control (Cont.)



Distributed Adaptive Controller

Decentralized adaptive control structure for turbofan system



x(t): state, spool speed
y(t): output, thrust
$u_{II}(t)$: fuel flow control input
$u_{I}(t)$: fan vane angle control input

Reference speed: $r_c(t) = [y_c(t) - y_{des} - d_3(u_3 - u_{3des})(\pi/180)]/c + x_{des}$

Decentralized adaptive control using combined fuel and vane angle control inputs

System II: Core Control Design

Plant model:

$$\delta\dot{x}_1(t) = a.\delta x_1(t) + b_1.\delta u_1(t), \quad \delta x_1(0) = \delta x_2(0) = 0,$$
$$\delta\dot{x}_2(t) = \delta x_1(t) - r_c,$$

Plant model:

$$\begin{bmatrix} \delta\dot{x}_1(t) \\ \delta\dot{x}_2(t) \end{bmatrix} = \underbrace{\begin{bmatrix} a & 0 \\ 1 & 0 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \delta x_1(t) \\ \delta x_2(t) \end{bmatrix}}_{X(t)} + \underbrace{\begin{bmatrix} b_1 \\ 0 \end{bmatrix}}_{b} u_1(t) + \begin{bmatrix} 0 \\ -1 \end{bmatrix} r_c(t)$$

Nominal PI Control:

$$u_{1lin}(t) = -K_f^T X(t), \qquad K_f(t) = [k_{pf},\ k_{if}]^T$$

Reference model:

$$\begin{bmatrix} \delta\dot{x}_{1m}(t) \\ \delta\dot{x}_{2m}(t) \end{bmatrix} = \underbrace{\left(\begin{bmatrix} a & 0 \\ 1 & 0 \end{bmatrix} - \begin{bmatrix} b_1 \\ 0 \end{bmatrix} K_f^T \right)}_{A_m} \begin{bmatrix} \delta x_{1m}(t) \\ \delta x_{2m}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \end{bmatrix} r_c(t).$$

Sys II Controller (fuel flow):

$$U_{II}(t) = u_{1lin}(t) + u_{1ad}(t) \qquad u_{1ad}(t) = K_f^T(t) X(t)$$

Adaptation law:

$$\dot{K}_f(t) = -\Gamma_f X(t) e^T(t) P \bar{b}, \quad K_f(0) = K_{f0} \qquad \Gamma_f = \Gamma_f^T > 0$$

N. Hovakimyan, Robust Adaptive Control Course Notes, University of Illinois at Urbana Champaign (UIUC), 2009.

System I: Fan Engine Control Design

Output (Thrust): $$\delta y(t) = c.\delta x(t) + d_2.\delta u_2(t) + d_3.\delta u_3(t)$$

Output Error: $$\tilde{y}(t) = y(t) - y_c(t) = c.\delta x(t) - d_2.\delta u_2(t) + d_3.\delta u_3(t) - y_c(t) \qquad y_I(t) = \int_0^t \tilde{y}(\tau)d\tau$$

Plant model: $$\delta\dot{x}_3(t) = y(t) - y_c(t) = c.\delta x_1(t) + d_3.\delta u_3(t) - y_c(t), \quad \delta x_3(0) = 0$$

Reference model: $$\delta\dot{x}_{3m}(t) = c.\delta x_{1m}(t) + d_3.(k_{ia}\delta x_3(t)) - y_c(t), \quad \delta x_{3m}(0) = 0$$

Sys I Controller (vane angle): $$U_I(t) = u_{lin}(t) + u_{ad}(t) \qquad u_{lin}(t) = -k_{ia}\delta x_3(t) \qquad u_{ad}(t) = k_a(t)\delta x_3(t)$$

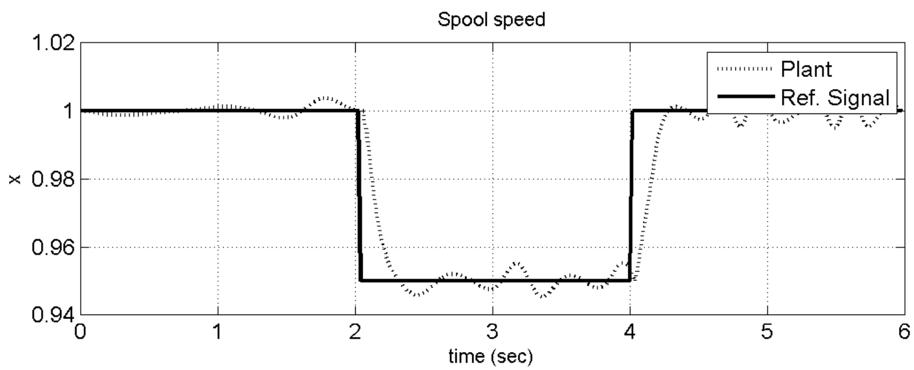
$$k_{ia} < 0$$

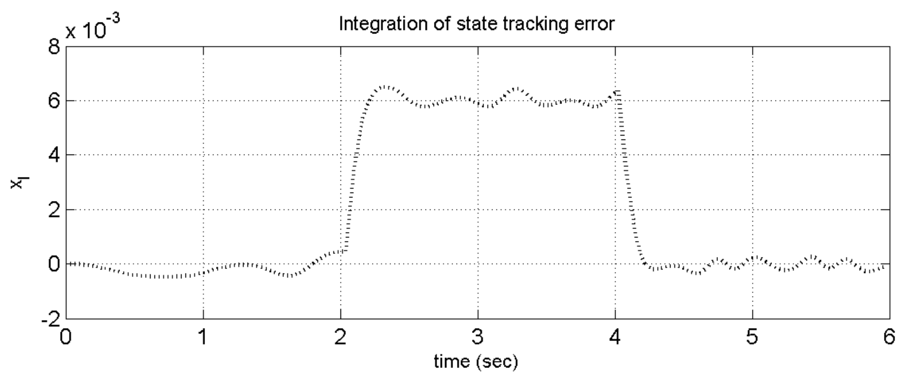
Adaptation law: $$\dot{k}_a(t) = -\gamma_a \delta x_3(t) e_3(t) sign(d_3), \quad k_a(0) = k_{a0} \qquad \gamma_a > 0$$

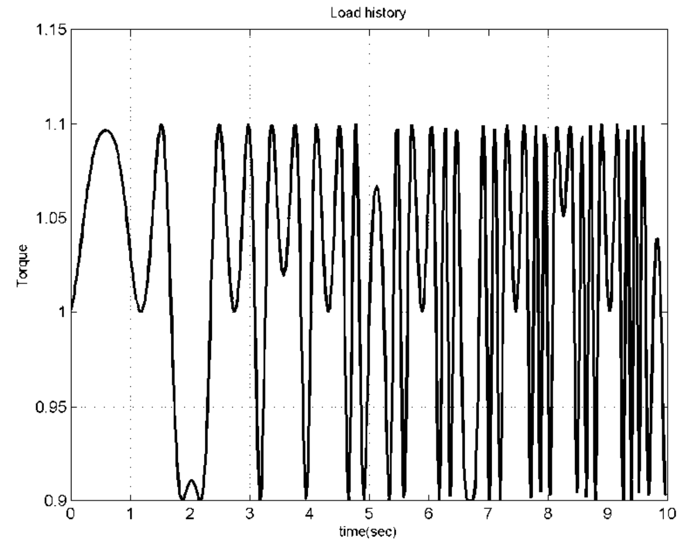
Ref.: N. Hovakimyan, Robust Adaptive Control Course Notes, University of Illinois at Urbana Champaign (UIUC), 2009.

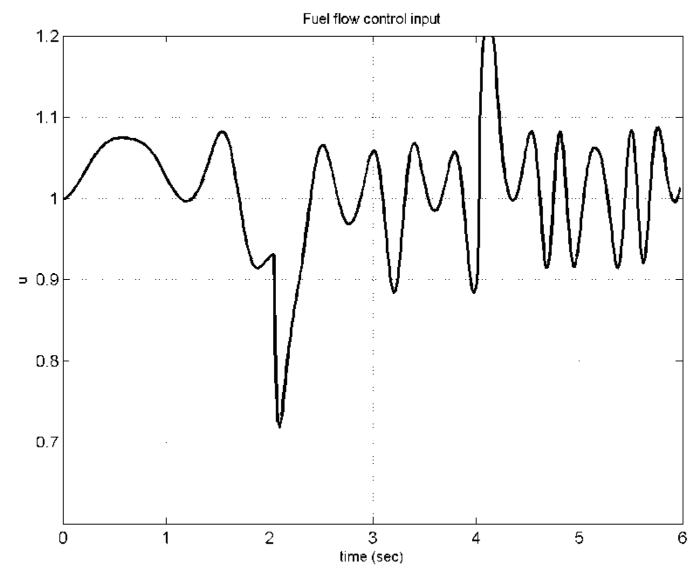
Simulation – Core Adaptive Control

$$T(t) = 1 + 0.1\sin(1.3(1+\sin(4t))t)$$

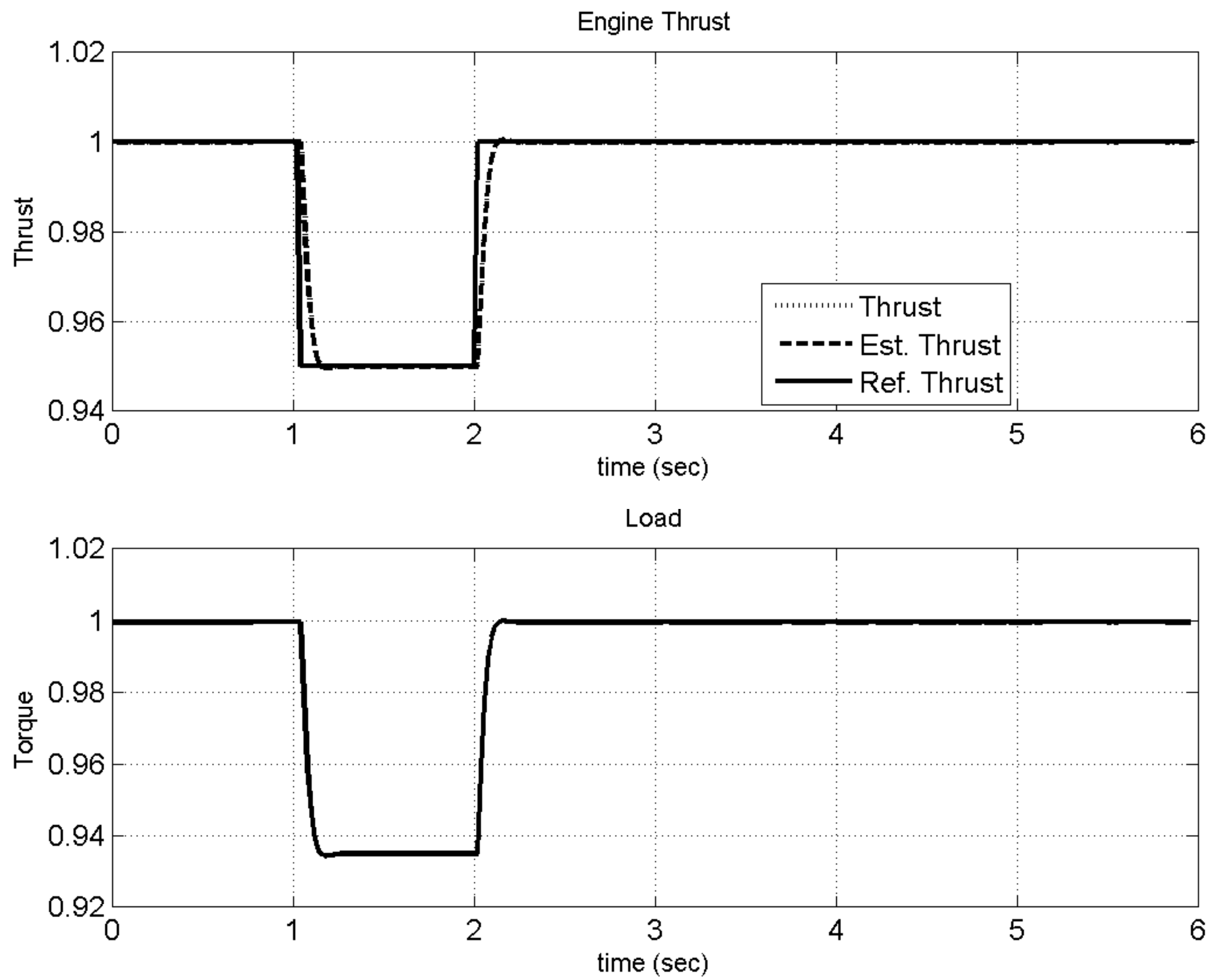




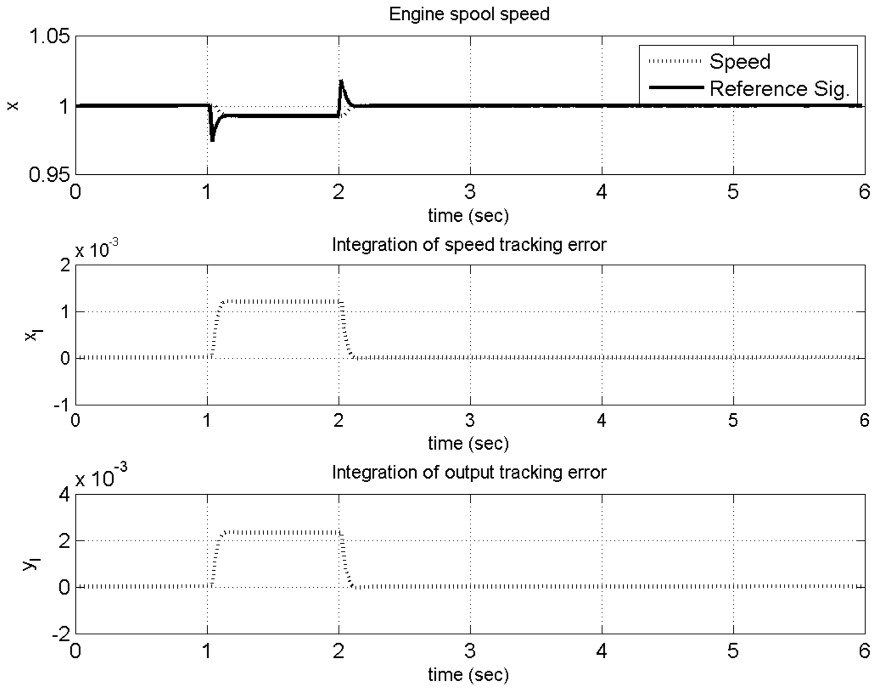


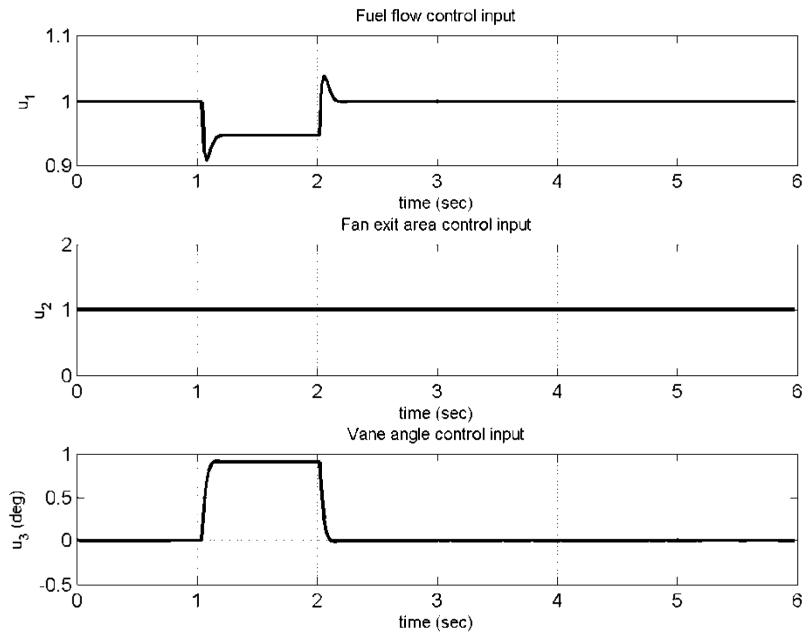


Simulation – Decentralized Adaptive Control

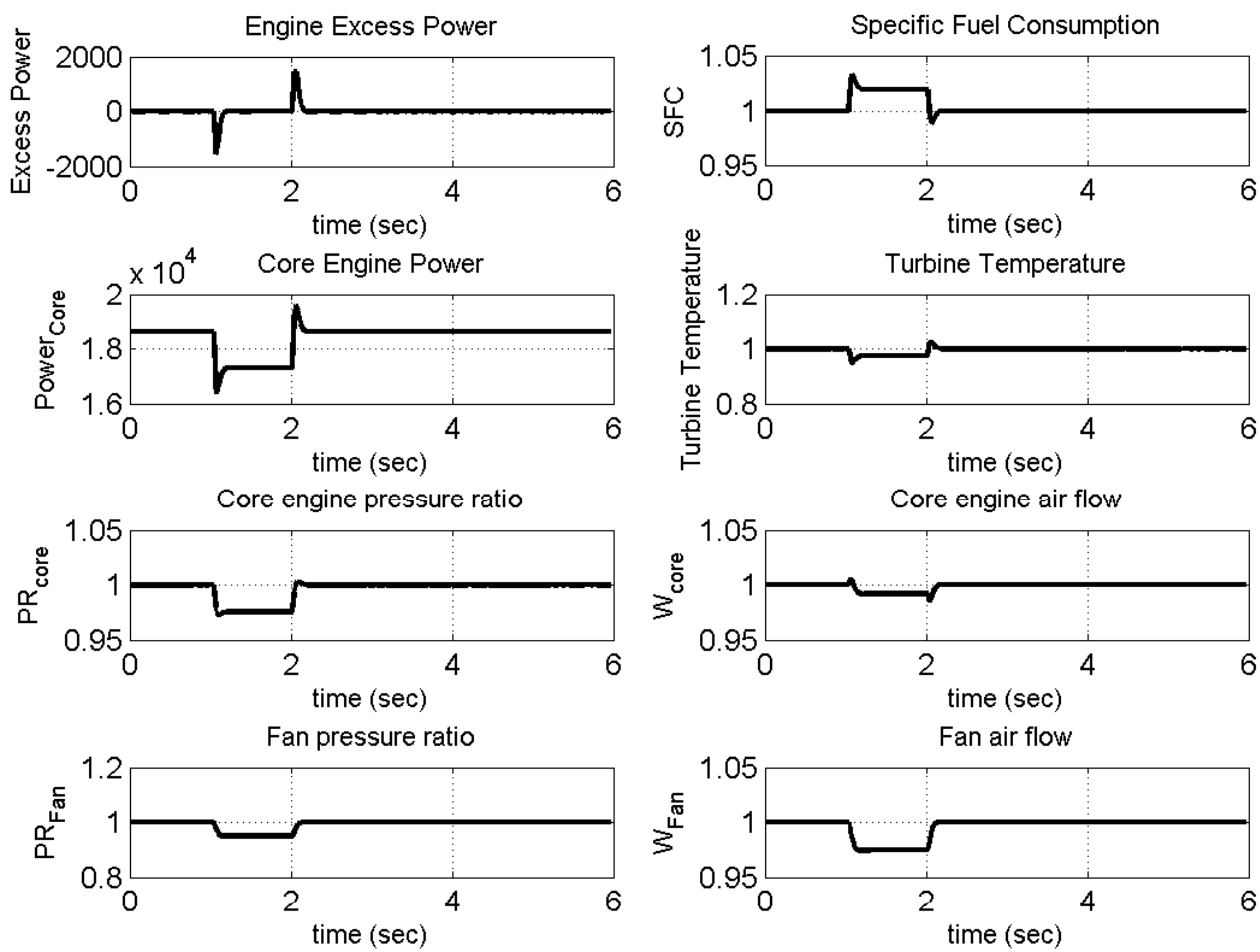


Simulation – Decentralized Adaptive Control (Cont.)





Simulation – Decentralized Adaptive Control (Cont.)



Summary and Future Work

Summary

- Stated Objective:
  - Research the control-theoretic issues associated with distributed control of non-homogenous systems containing adaptive components. Develop the functional architecture of a distributed control system in a gas turbine application.
- Progress: Demonstrated distributed adaptive control of a simulated turbofan type engine.
  - Developed dynamic turbofan engine model
  - Demonstrated linear distributed control
  - Demonstrated adaptive distributed control of engine
- Future goal is to demonstrate distributive adaptive control on a real engine
  - GE-80 developing gas turbine driven variable pitch fan
    - Program pending

Future Tasks

- Dealing with Networked Control System (NCS) issues
  - Packets dropout during transmission and/or incomplete multiple-packet transmission
  - Network induced delays: sensor-to-controller delay and controller-to-actuator delay
  - Bandwidth limitations
  - The insertion of the communication network in the feedback control loop makes the analysis and design of an NCS complex.

Future Tasks Required for Live Engine Test

- Engine control laws for off-design conditions
  - Starting
  - Steady-state part-power control at various throttle settings
  - Full-scale throttle transients (idle-to-max, max-to-idle, etc)
  - Temperature, pressure, altitude variation accommodation
- Control laws for fault detection and safety
  - Sensor/actuator failure recognition and accommodation
  - Implementation of mitigation strategies for over-speed, surge, etc to prevent catastrophic hardware damage
- Hardware integration
  - Controller/sensor/actuator bandwidth requirement definition
  - Real-time embedded system details

Backup Slides

Turbofan Model (Cont.)

Noting that the power output of each of those components is defined by $\mathcal{P} = \mathcal{T}\omega$

and expressing the key parameters as a fraction of the design value, previous eqn can be rewritten as

$$\frac{\dot{N}}{N_{des}} = \left(\frac{60}{4\pi^2}\frac{\mathcal{P}_{des}}{IN_{des}^2}\right)\left(\frac{\mathcal{P}_t}{\mathcal{P}_{t,des}}\frac{\mathcal{P}_{t,des}}{\mathcal{P}_{des}} - \frac{\mathcal{P}_c}{\mathcal{P}_{c,des}}\frac{\mathcal{P}_{c,des}}{\mathcal{P}_{des}} - \frac{\mathcal{P}_f}{\mathcal{P}_{f,des}}\right) / \left(\frac{N}{N_{des}}\right)$$

where rotational speed (N) has been expressed in rpm instead of rad/s.

Compressor/fan power, written as a fraction of the design power,

$$\frac{\mathcal{P}_c}{\mathcal{P}_{c,des}} = \frac{W_2}{W_{2,des}}\frac{P_2}{P_{2,std}}\sqrt{\frac{T_2}{T_{2,std}}}\frac{\eta_{c,des}}{\eta_c}\frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\pi_{c,des}^{\frac{\gamma-1}{\gamma}} - 1}$$

Turbine power can be calculated as a function of the turbine inlet temperature. Written as a fraction of the design power,

$$\frac{\mathcal{P}_t}{\mathcal{P}_{t,des}} = \frac{W_c}{W_{c,des}}\frac{P_2}{P_{2,std}}\sqrt{\frac{T_2}{T_{2,std}}}\frac{\eta_t}{\eta_{t,des}}\frac{1 - (\pi_c\pi_b)^{\frac{-(\gamma-1)}{\gamma}}}{1 - (\pi_{c,des}\pi_{b,des})^{\frac{-(\gamma-1)}{\gamma}}}$$

Turbofan Model (Cont.)

For the fan and compressor, the pressure ratio and efficiency of each component is expressed as a function of the spool speed and air flow, both corrected to inlet conditions. The change in incidence angle of the fan blades from the design condition (delta-i) is also input to the fan map.

$$\left[\frac{\pi_c}{\pi_{c,des}}, \frac{\eta_c}{\eta_{c,des}}\right] = CompressorMap\left(\frac{W_c}{W_{c,des}}, \frac{N}{N_{des}} / \sqrt{\frac{T_2}{T_{std}}}\right)$$

$$\left[\frac{\pi_f}{\pi_{f,des}}, \frac{\eta_f}{\eta_{f,des}}\right] = FanMap\left(\frac{W_f}{W_{f,des}}, \frac{N}{N_{des}} / \sqrt{\frac{T_2}{T_{std}}}, \Delta i\right)$$

For the purposes of the Phase I investigation, generic maps have been generated for the fan and compressor based on assumed phi/psi characteristics and other aspects of compressor theory.

Thrust As a function of design parameters:

$$\frac{F}{F_{des}} = \frac{A_e}{A_{e,des}} \frac{P_2}{P_{2,des}} \frac{\pi_f^{\frac{\gamma-1}{\gamma}} - 1}{\pi_{f,des}^{\frac{\gamma-1}{\gamma}} - 1}$$